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Characterising the Creative Behaviour of Designers within the Late-Stage Engineering Design Process

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Summary

Creativity is widely recognised as a vital element in modern-day engineering design. It is through creative behaviour that engineering designers produce creative solutions to their problems, and through creative solutions that many companies succeed. However, research into creative behaviour within engineering design has to date focused largely on the design process in general or on early-stage design; neglecting the often complex and constrained engineering practice that occurs during later design stages. It is to this research focus that the work presented here has been completed.

Defined through its production of outputs that are original, of appropriate quality, and surprising, creative design behaviour is a culmination of several aspects within the engineering process; that of a person or team; working within a specific context; actively completing a process; that will produce an output for a particular design brief. At the centre of this situation is then the designer; it is through their individual behaviours that creative outputs are formed.

Due to the nature of the later stage engineering design process, the accompanying influences under which designers work, and the types of activity that they complete, it presents a very different situation to early-stage design. It is therefore not possible to assume that understanding based on study of either early-stage design or the design process in general is entirely applicable to later-stage design processes or to the type of support that designers working within may need. Thus, when linked to creative behaviour, this presents an opportunity for research; there is possibility to gain valuable understanding of the manner in which creative solutions are produced through the study of designers' creative behaviour in later-stage design. It is to this goal that this research has been performed, namely to characterise the creative behaviour of designers within the later-stages of the engineering design process.

To this end, this thesis presents a detailed review of the field of creativity, the field of engineering design, and current understanding of designer behaviour. From the understanding that each of these provides, a framework and coding scheme are then developed, which are designed to identify creative behaviour within the individual tasks of designers throughout the design process. This coding scheme is then used within three studies; one based on seven less-experienced designers working within a 22-week project, one of eighteen designers of varying experience undertaking a design brief set by the author, and one of four designers working within industry.

Through analysis of the data produced by these studies, this thesis contributes several characterisations of designer behaviour within later-stage design. These include typical task-types in which all designers are creative, two distinct creative approaches that correlate with a designers personal creative style, and types of tasks to complete in order encourage streamlining of the design process; in addition to more general characterisations concerning designer focus within early and late-stage design, and differences in behaviour between expert and less-experienced designers.

Through the understanding that this research has gained and presents within this thesis there are many opportunities for further work on the subject of the improvement and support of designer behaviour. Both within an academic and industrial context, detailed and specific characterisation of creative behaviour in later-stage design has the potential to provide the means to improve both the process and output of engineering design.

Acknowledgements

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Publications

The following papers have been published as an output of work completed within this thesis.

Journal

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Snider, C. M., Culley, S. J., & Dekoninck, E. A. (2013). Analysing creative behaviour in the later stage design process. Design Studies, 34, 543-574.

Conference

Snider, C. M., Dekoninck, E. A., & Culley, S. J. (2014). A study of creative behaviour in the early and late stage design process. In DESIGN 2014: The 13th International Design Conference. Dubrovnik, Croatia.

Snider, C. M., Culley, S. J., & Dekoninck, E. A. (2013). Determining relative quality for the study of creative design output. In ICoRD'13: International Conference on Research into Design. Chennai, India.

Snider, C. M., Cash, P. J., Dekoninck, E. A., & Culley, S. J. (2012). Variation in creative behaviour during the later stages of the design process. In ICDC2012: The 2nd International Conference on Design Creativity. Glasgow, Scotland.

Snider, C. M., Dekoninck, E. A., & Culley, S. J. (2012). Improving confidence in smaller data sets through methodology: The development of a coding scheme. In DESIGN 2012: The 12th International Design Conference. Dubrovnik, Croatia.

Snider, C. M., Dekoninck, E. A., & Culley, S. J. (2011). Studying the appearance and effect of creativity within the latter stages of the product development process. In DESIRE'11: The 2nd International Conference on Creativity and Innovation in Design. Eindhoven, Netherlands.

Snider, C. M., Dekoninck, E. A., Yue, H., & Howard, T. J. (2011). Analyzing the Use of Four Creativity Tools in a Constrained Design Situation. In ICED11: The 18th International Conference on Engineering Design. Copenhagen, Denmark.

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Nomenclature

Activity: Concerned with the design process rather than the design itself, this term describes discrete elements within design process stages with a single specific goal, such as determination of design requirements or selection of design layout (see Section 3.2).

Approach: The manner in which behaviour is completed (see Section 3.2).

Behaviour: The mental and physical tasks completed by a designer over time, through which individual activities are completed (see Section 3.2).

Creative: Elaborated upon in detail within the work, in general terms creative refers to the characteristics of originality, appropriateness and surprise; each of which will be evident in the subject that is being described as creative (see Chapter 2).

Creativity: A generalised term used to provide reference to the field of creativity as a whole and the facets that it contains, including all current research, practices and understanding (see Chapter 2).

Design: *verb:* the process of creation, to form a plan or scheme, to conceive and arrange.

Noun: a physical or virtual object, the subject that forms the output of a design process. This is true regardless of the completeness of the design from a preliminary stage through to a finalised stage.

Designer: The human performing and passing through the design process. It is through the designer and their behaviour that the design process occurs and the output is produced.

Design Process: The series of steps by which a design is created, from the initial point of ideation to the point of production (see Chapter 3).

Expansion: The act within a designer task that indicates creative behaviour. As elaborated within Section 2.4, expansion is evidenced by exploration of variables and knowledge that are for use within the design process, or exploration in the manner by which they may be used.

Output: The physical result of a design process.

Task: Concerned with the production of the design itself by the designer within the design process, this term describes the discrete elements within a specific activity, each with its own specific goal, such as individual calculation, individual application of layouts or gathering information regarding a specific subject (see Section 3.2).

The important thing is not to stop questioning.

Curiosity has its own reason for existing.

Albert Einstein (1879 – 1955)

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Chapter 1: Introduction

In the modern world of science, information and technology, it can be difficult to see just how humble the beginnings of humanity once were and the driving forces behind its rise to the modern day. In the past two decades, the internet has become a common household feature. Twenty years before that, the mobile phone revolutionised the way we were able to communicate. It is only one hundred years since the pioneers of flight, 300 years since Benjamin Franklin and his study of electricity, 700 years since the western use of gunpowder, and 800 years since the introduction of the Gutenburg printing press (Marr, 2013). This brief flash of existence has encompassed thousands of years of civilisation and progress. Agriculture, domestication, the written word; throughout history there is evidence of the growth of humanity, but also evidence of the ability that has allowed and inspired its growth and survival.

In the eyes of some (Brown, 2012), it is the use and development of tools that has driven human evolution. Through the development of society, methods of hunting and provision bolstered survival; when society grew larger, settlement and agriculture provided food and support; as tools made survival easier, focus could drift towards curiosity, intelligence and discovery. Through all of these, humanity has been supported and enabled by what it has produced. With invention and discovery the pace of development can accelerate, using tools both as an aid and as a basis for further improvement. When a need has arisen, humans have produced what was needed to meet it, and when an opportunity has appeared, humans have invented the technology to take it.

From the moment a nearly hairless ape on a plain turned the most primitive of tools to their use, humanity has been sustained and driven through our ability to create, and to design.

1.1 Design in a Modern Context

As society has developed, the purpose of design has arguably changed dramatically. Beyond the ancient use as a reaction to necessity, design today reflects a range of desires for everything from everyday items, to luxury status symbols, to complex tools and machinery. This wide scope has led to a great breadth, encompassing fields from the highly aesthetic to the highly technical.

Of the more significant of these is the field of engineering design. To support this £99 billion industry (ONS, 2013) within the UK requires a wealth of skills and resource; the ability to generate ideas, the skills to develop them, the tools and machines to prototype and test them, the factories to produce them on a large scale, and much more.

At the core of all of these remains the common thread of design and of the designer. Behind each idea or development there is a person or team of people who turned it into a tangible product or system; behind every product or system there is a person or team who designed every piece of tooling and machinery involved in its manufacture; and the same again for every factory, every delivery vehicle and every point of sale.

It is this scale and breadth of engineering activity that has made the study of design within the context of engineering worthwhile. Through the understanding of the designer and design process, it is the goal of research to provide the knowledge and tools to support and improve each aspect; the process of creation, production, management and the design output in itself.

1.1.1 The Dual Nature of Design

One pattern that can be seen both in the study of design and in the study of creativity, the two central themes of this research, is the diverse use and understanding of the terms that define the fields. Design as a term can reference both the noun of design as an output (such as a sketch, a painting, or a blueprint), and the verb of design as a process (producing, for example, any of the previous)(OED, 1989).

This dual nature has important and potentially significant consequences. Particularly within the generally solution-focused domain of engineering (Lawson, 1994), it is the result that is of greatest importance. A commercial company's success in many cases is defined by their profit and share of the market, which in turn is generated through the commodity, service or physical product that they are providing. Particularly within companies that deal in more tangible and physical outputs, it is therefore design as an output that is their driver for success.

But as stated within the definition of the OED, design is also a process; and it is as a process that design can have a substantial impact on the success of a company. As example, in some cases the design process may require a relatively small or individual outlay, but can often reach very high economic and time commitments (such as the reported $6 billion development cost of the Ford CDW27 platform (Kobe, 1995)). Research has shown that as high as 75% of final product cost can be a result of design process costs and commitments (Ullman, 1997, Ulrich and Pearson, 1993, Barton et al., 2001). Within each design process there are also what can be thought of as multiple levels to consider, from a high, systems level, to the detailed components and sub-systems. It is therefore essential for any product-producing company that not only is their design output of sufficient standard, but that their design process is effective and efficient (O'Donnell and Duffy, 2002).

The goals for design research must encompass and consider both of these aspects. Through study and understanding research can increase both the actual output of any engineering designer's process, and indeed the process itself.

1.1.2 The Wider Context of Industry

As demonstrated by the wide range of engineering design-based industries in existence today, design is a central tenant and enabler of modern living. The demand for commercial products and systems has provided a broad spectrum of opportunities around which many businesses, both large and small, have been built.

In all cases, regardless of scale, major challenges exist and must be overcome. For example, a small business may find the high cost of prototyping and initial tooling is prohibitive, while a large business may find that the prevention of defects in production may prevent millions of pounds of delay and re-work (see Snider et al., 2013a). Coupled with the direct practicalities of their production, companies must also be mindful of myriad external variables that affect their process and results, such as the constantly evolving emissions requirements of the automotive industry (EP, 2009), or the role of intellectual property in the telecommunications industry (Anon., 2012). In other parts of the market, disruptive design technologies such as rapid prototyping (Cash et al., 2013)] and financial support and distribution through online channels such as Etsy (www.etsy.com) and Kickstarter (www.kisckstarter.com) are evolving the marketplace. Design and distribution can now occur on a smaller scale than previously possible, to a wider market with interest and expectation.

The design industry is then of great diversity. At one end of the spectrum there are small businesses taking advantage of the accessibility of modern design and distribution methods to create and release their products. At the other, larger companies are working within incredible complexity. Such breadth, responsibilities and challenges reinforce the need for deep understanding of design processes and support, as well as management of designers. Only through careful development can the complex world of engineering design continue to improve.

1.2 Design Research

It is to the end of improving the process of engineering design that the field of design research exists. Over the past half century a growing group of researchers have been dedicated to such topics as design models (Pahl and Beitz, 1984, Pugh, 1990), creativity (Dorst and Cross, 2001, Gero, 1996), systems design (Blanchard et al., 1990), computational design (Maher and Poon, 1995), and more; in an effort to build new knowledge structures that increase understanding, provide support, and improve output (Horvath, 2004).

Considering the nature of design, which forms an unusual and complex form of problem formulation and solving activity (Dorst, 2006, Simon, 1973), design research has proven worth as a field in its own right, with much overlap from diverse fields such as natural sciences, social and behavioural science, humanities, and the arts (Friedman, 2003). This breadth provides opportunities for many forms of research and for drawing from the work of others, creating a field that is diverse in its study, methodology and output (Finger, 1989a, Finger, 1989b).

In order to characterise and reflect real-world occurrence, design research commonly relies upon empirical means (Horvath, 2004), such as designer observation and protocol study (Blessing and Chakrabarti, 2009), to provide experimentally-derived validation of theory and to address the complexities abounding in the human-centric study of the designer as the centre of the design process. It is this approach that is utilised within this work, elaborated within Chapter 5.

1.3 Models of Engineering Design

Many engineering projects are multi-national affairs with hundreds of engineers working in plants around the world, requiring careful control and management of designers and communication. Products too can get exceedingly complex and present their own challenges, from the high complexity of a plane with many thousands of components to the high production rate of a simple drinks can at many thousands per minute. One major approach to understanding and managing this issue within design research has been description and modelling of the engineering design process (see Pahl and Beitz, 1984).

These models typically describe a general case. Although individual difference in the high-level processes of engineering design will exist due to, for example, product and company, and indeed the individual processes of designers will vary even when the high-level process is the same (as will be demonstrated within this work), it is through description in an abstracted sense that broad applicability of research has been achieved. These models describe engineering design on a multitude of levels of granularity, showing how the engineering design process may be considered in general and broken down into its constituent parts; the processes, activities and tasks that must be completed for the process to pass from ideation to finalisation.

Broadly studied by a range of researchers at a range of levels of abstraction (see, for example, Pahl and Beitz, 1984, Pugh, 1990, Dieter and Schmidt, 2009, Tomiyama et al., 2009, Hatchuel and Weil, 2003), the engineering design process has been described in many different ways and with varying focus, although when directly compared similarities are strong (Howard et al., 2008a). In a general sense, the engineering design process can be broken into four core phases; task clarification, concept design, embodiment design and detail design (Figure 1); discussed in detail within Chapter 3.

1.3.1 The Stages of Design

The design activity represented by these models is a process that exists to produce a discreet artefact or service, an output that can be considered the end process result. Typically, the design process is defined through four stages (Figure 1).

As will be elaborated upon within Section 3.3, this work defines each design stage by purpose; the end goal of each stage through which the designer completes the whole process. This view is not unusual within the literature, with similar interpretations including that of Huang and Kusiak (1998) and Howard *et al.* (2008a); while influences can be seen from the work of Gero (1990), Pahl and Beitz (1984) and Deiter and Schmidt (2009). In general, models of design describe four distinct stages, each with a different purpose and different characterisitics.

Task Analysis

Here, the designer or design team must determine the purpose of the design, identify and understand the problem, and perform research that will allow them to continue. Additionally, they must determine in a basic sense what functions the product or sub-system will need to complete in order to fulfil the purpose. There is little direct, physical consideration of the product at this stage, instead concentrating on the background and context in which it will exist.

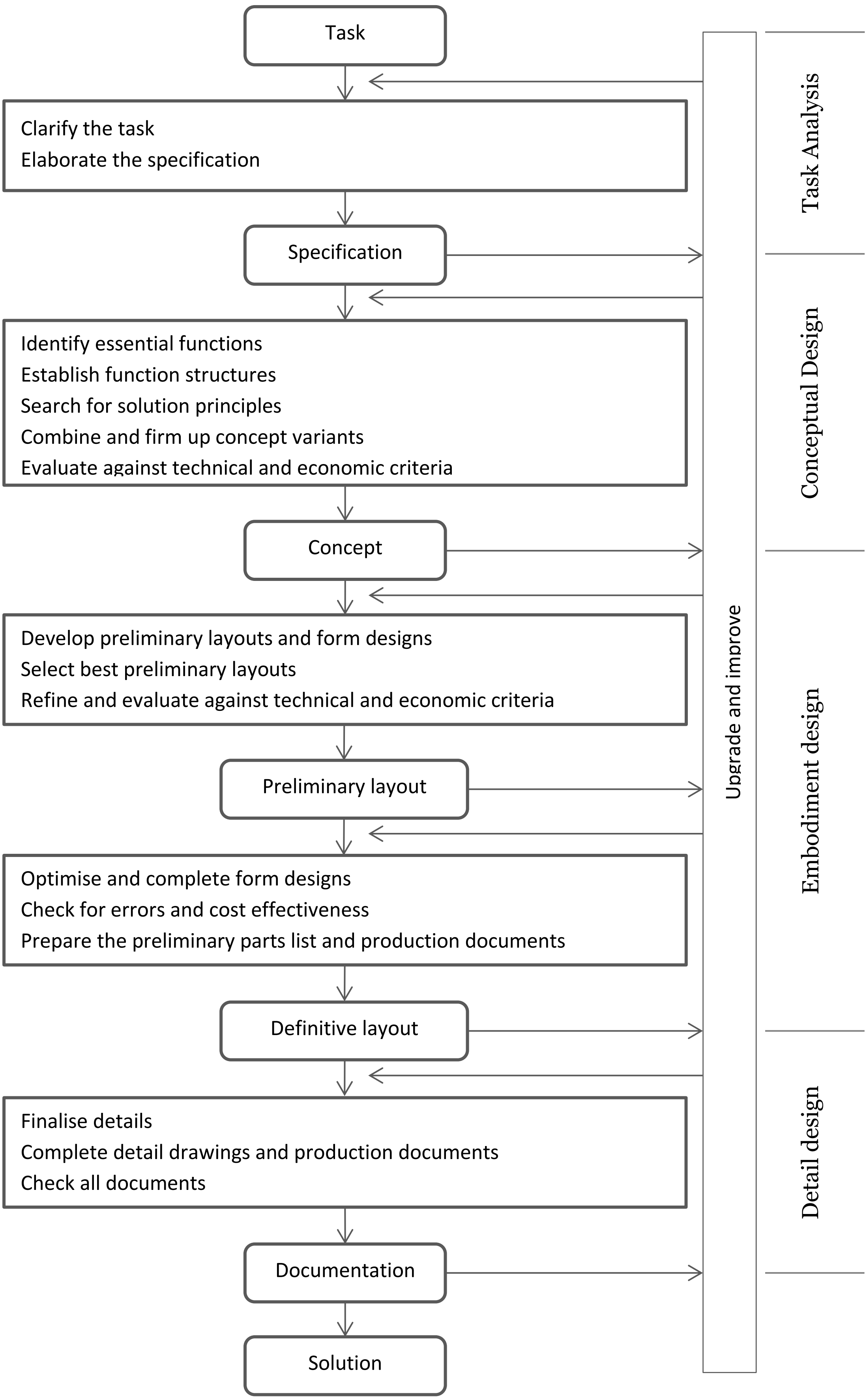


Figure 1: The engineering design process (Pahl and Beitz, 1984)

Concept
The purpose of this stage is to determine what functions are needed to complete the product purpose and what technologies or systems could be utilised in order to complete each function. As a necessity to this, preliminary definition of the behaviour of the product will occur, designing the inclusion of various technologies within the overall system. This enables the designer to work out in general terms the method by which the final product will complete its function.

Embodiment
The purpose of this stage is to design, in detail, how the product will behave to complete its function. This includes detailed description of the layout of the components, how they will interact and how, together, they can contribute to both the functions of the sub-systems and the overall function of the product. This process will also include preliminary design of the structure of the product, including basic sizing of components, appropriate analysis of any forces or stresses, and ensuring feasibility of assembly.

Detail
The purpose of this stage is to determine the structure of the product in detail, including detailed dimensioning of all components, all calculations and analysis that must be performed and fixings and interface design between components or sub-systems; as well as tasks such as designing components for ease of manufacture, minimal cost, or minimal material use.

1.3.2 Variation throughout Design Stages

Clearly, the specific activities of design can vary significantly between each design stage. As detail increases, so the quantity of constraints under which the designer must work increases (McGinnis and Ullman, 1990) and potentially the complexity of the design problem (Eckert et al., 2012, Eckert et al., 2004). There is also a shift in focus from solving the function of the design to developing its detailed structure (Howard et al., 2008a, Gero, 1990), and from open design to more iterative or variant design processes (Eckert et al., 2012).

In some research areas, the later stages of the design process have been given a great deal of attention. Computationally, researchers have attempted to devise systems of optimisation for layout and configuration (Scaravetti et al., 2006, Chenouard et al., 2009), or use the known constraints of a system to automatically synthesise a solution. However, there has been little research in these later stages when specifically considering designers and their behaviour, instead focusing on behaviour in a general sense (see Dorst and Cross, 2001, Cross, 2004a) or in early stage design. Currently, at the centre of the design process resides the designer, complete with individual difference, variation, and potential for support and improvement throughout their design process.

1.3.3 The Behaviour of Designers

While the pivotal, central role of the designer exists, it is vital to increase the understanding of behaviour, its enhancement, its support and its management. To this end, much research has studied human (designer) behaviour within the specific context of design. Due to the nature of design as ill-structured problem solving (Dorst, 2006, Simon, 1973) it can be considered separate to much research, thus defining a context worthy of study in its own right.

Through their behaviour (the sequence of tasks and activities that they complete, Section 4.1), designers will transition a concept from an initial state to one of higher detail and development.

This may entail complete development from an initial idea to full production, or may equally include a smaller, more specific activity within a larger design team and larger design project. By capturing and understanding this transition, details of consistently appearing behaviours, beneficial behaviours, and perhaps detrimental behaviours can be identified. Such knowledge can then be explored and used pro-actively to support and enhance designer behaviour, potentially leading to an enhanced result in terms of both the final product and the process followed.

1.4 The Subject of Creativity

As will be discussed in Chapter 2 and summarised here, the field of creativity research provides a structure of understanding through which the engineering design process and the behaviour of designers within can be studied.

Very similar in nature to the definitions of design as both a noun and a verb, creativity is often considered to apply both to the process of design, and to design as an output. This dual applicability is broad reaching throughout the field of design, often used quite loosely, but does have extensive consequences both for research, and for engineering design itself.

While it is understood that the engineering design process is a means of creation, it is important to highlight the distinction between that which is *created*, and that which is *creative.* While the former implies the definition of the term in its basic verb form – to bring into being or cause to exist (OED, 1989) – the use of the term *creative* implies a higher level of intent, and refers to the effort of a human designer to do more than create alone; they intend to produce something novel and appropriate (Sternberg and Lubart, 1999), beyond the expected solutions that others may simply bring into being. Thus consideration of the ability to be *creative* within the engineering design process, and so the production of highly beneficial solutions within, requires deeper understanding of the complex topic of creativity itself, and the role it plays in context.

As a research topic, creativity is recognised to be complex and difficult to understand (Amabile, 1996, Boden, 2004). As a term it is broadly used in a variety of domains and design situations, both those typically more qualitative and those more empirical (as within this work). This complexity, variation in use and meaning, and requirement to consider context all complicate the study of creativity as a singular concept. Thus, the four pillars of Rhodes form a structure that allows understanding of the complex subject of creativity, as described below.

1.4.1 The Four Pillars of Creativity

The complication in the understanding of creativity has led to somewhat of a reputation as a wide-reaching and intangible subject, used loosely to describe a wide variety of things from individuals, to their actions and to the eventual outcomes. Such a concept is very difficult to study singularly and in depth, and so its many facets are often separated into smaller areas that are more easily managed through a variety of methods of study (Runco and Sakamoto, 1999). As such, creativity itself has not been defined in all-encompassing terms, but rather in more specific breakdowns of its generally accepted usage (Sternberg and Lubart, 1996).

As proposed by Rhodes (1961), one such breakdown is into four separate categories, termed the four *pillars of creativity* (see Figure 2). According to Rhodes, each of these strands provides an insight into creativity, but only through all can it be understood.

The Creative Person

The pillar of the creative person focuses on the various qualities of the practitioner; including such areas as behaviour, intellect and attitude. Detailed research over many decades has covered these factors and their overall influence on what is deemed to be a creative person (or to develop a creative person); ranging from the understanding of creativity in a personal sense and in more general terms, such as into the correlates between creativity and intelligence or giftedness (Barron and Harrington, 1981, Terman and Oden, 1959), the effect of personality (Feist and Barron, 2003, Feist, 1999) and the effect of personal growth (Helson and Pals, 2000). Within the domain of design, much research within this area has looked at subjects such as expertise, describing the personal characteristics required to generate a creative product (see Cross, 2004b, Cross, 2004a).

The Creative Product

The pillar of the creative product focuses on the output to be produced, communicated or subjected to judgement; once it is of a tangible form. At a higher and more abstract level, this can be an idea or theoretical concept from which products may eventually spawn, such as the theories of electromagnetism that led to invention of radio and television. At a more concrete level, this can concern any specific product or invention that has brought a new outlook and a new perception (e.g. the multiple technological integrations within the mobile phone, each bringing a new aspect of usability or novelty). Research into this area has focused on aspects such as what defines a product as creative (Chakrabarti, 2006, Howard et al., 2006) and metrics by which a product can be assessed (Sarkar and Chakrabarti, 2011, Shah et al., 2003, Chakrabarti and Khadilkar, 2003). These commonly include novelty; value or appropriateness (Sternberg and Lubart, 1999); and another factor in reference to the unexpected or surprising nature of the product (Macedo and Cardoso, 2002, Gero, 1996). Despite its familiarity as physical in nature within the field of engineering, it is important to note that product here refers to the output of a process, regardless of form. It is in this latter sense that the term is used throughout this work; the output of any process is synonymous with the product of any process.

The Creative Process

Referring to the process of the act of creativity, this pillar takes into account both the direct process that a person will follow and the factors that influence it (and to which a person's process is inextricably linked). Research in this area has typically looked at the types of methods that a person may follow, and hence what a designer may do should they wish to develop a creative output (Shneiderman, 2000, Lubart, 2001, Wallas, 1926); and the behaviour of designers through the design process (Bender and Blessing, 2004, Motte et al., 2004b).

The Creative Press

The press is an unusual term coined by Rhodes (1961), and refers to the relationship between the person and their environment in both a personal sense and a larger scale cultural sense. Thus it refers to the variety of influences external to the person, or to the design and design process.

For the sake of more commonly used terminology, this work replaces the term *press* with *context*, describing all external circumstances concerning creativity. As such, elements that influence the creative context could range from the office environment, to the team dynamic and support that the designer receives, to the national economic situation and political context. Research in this area has looked at what allows a creative idea, creative person or creative process to perform at their best, or the cultural, field and domain factors through which creative ideas come about (Csikszentmihalyi, 1999, Amabile et al., 1996). As discussed in Section 2.5, this pillar plays a smaller role within this work in order to focus in detail on the person, product and process, but is considered specifically in Chapter 10.

As will be explored in Chapter 2, through the four pillars it is possible to provide structure to the study of creativity in context of its influences, classification and purpose.

1.4.2 Creativity within Engineering Design

Reflecting on these four pillars, engineering design maintains a fairly specific focus throughout the domain - that of the need to produce a product as solution to a specific problem. Engineering design creativity will always appear according to this general structure, considering a design process being completed by a design practitioner to produce a design output.

In this sense creativity within engineering design is really a means to an end, rather than an end in itself. In contrast to other fields where creativity may be a requirement of success, engineering design is indifferent to creative occurrences during production, instead focusing on efficient and effective execution. Any output is judged by its completion of specification and as an appropriate solution to the initial problem; with creativity as a non-necessary element that may be of benefit along the way. This consistent structure provides a basic conceptual framework for the study of creativity in engineering design; as a coincident factor occurring in tandem to engineering design or its output.

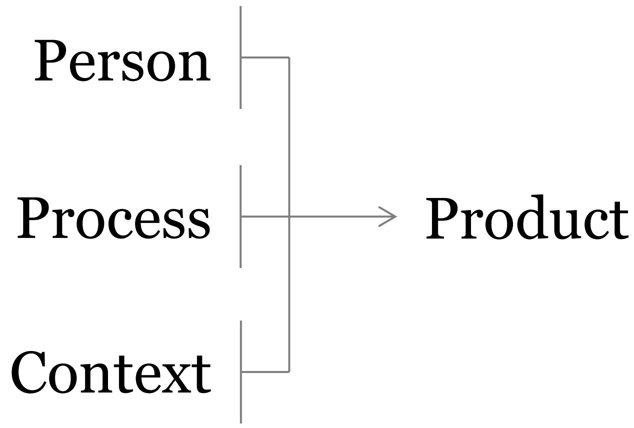


Figure 2: The four pillars of creativity within engineering design, adapted from Samuel and Jablokow (2011)

Understanding this, the desire or need for creativity within engineering can be considered to vary. Depending on many elements of circumstance of each specific case of design, it may equally prove beneficial to be non-creative in design as it may to be creative. As example, when available budget and time are low, the traditional understanding of creativity as a step of exploration may prove unfeasible, or when working in a highly complex design environment a drastic change in configuration may lead to high change propagation and cost (Eckert et al., 2012, Eckert et al., 2004).

The desire for creativity in engineering design can then be considered from two perspectives (see Figure 3). In one case, some form of creativity may be as a reaction to the occurrence of a problem or difficulty in design, and therefore as a potential necessity for continuation. In the second perspective, as discussed within the trends of evolution and S-curves of the TRIZ methodology (Altshuller and Rodman, 1999), a high increase in performance of a product during its evolution may require a break away from variant design or iteration of past solutions. In such cases, creativity is the catalyst that allows substantial benefit in output to be formed; pushing to produce a better solution than currently exists. By exploring and introducing new technologies or solution principles, significant gain may be introduced to the product that would not be implemented without creative behaviour.

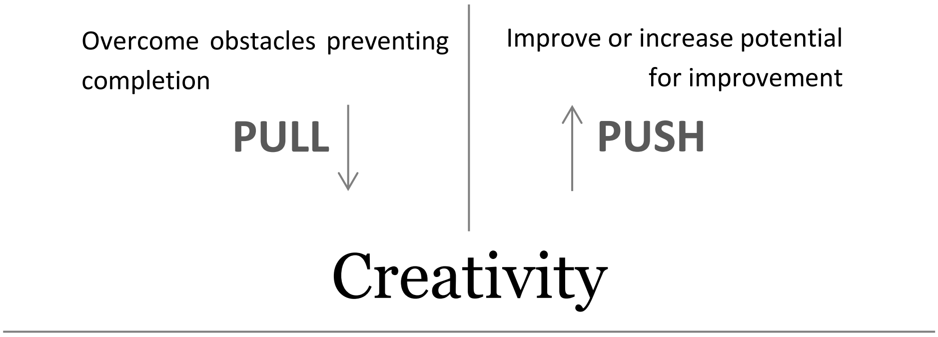


Figure 3: Desirability for creativity as a push or pull

The study of creativity within engineering design then demonstrates clear potential for benefit and impact. Both in terms of overcoming issues that arise within the design process and in terms of improving the output, the field of creativity presents broad potential for benefiting engineering design.

By considering the role of creativity as parallel across both perspectives, it becomes a means to an end goal of benefit for all aspects of design, be it person, product, process or context.

1.5 Creative Designer Behaviour

One truism of engineering design, and also one factor that makes the field most interesting, is that it is very broad in the scope of its output. This fact makes study of engineering design in context of the product a complex activity; if the output can vary dramatically, so can all elements in relation to it. For any research to be generalisable across design situations it is therefore important that it is product-independent, and that the results it produces are consistent and valid in as extensive a spectrum as possible. This is also true from the perspective of creativity research. To allow study to be generalizable across products, there must be a focus on the pillars of person, process and context; considering the pillar of creative product in terms of those characteristics that are common across outputs. This view is one that is the basis of this work. In order to maintain wide applicability of findings, focus lies not solely on the output, but on the designer and the process that they complete.

1.5.1 Research into Creative Behaviour

Given the role of creativity within engineering design as of potential benefit but not always of necessity, particularly in the later-stages as highlighted above, it presents an unusual and useful opportunity for research.

When creativity is considered a means to an end, as an occurrence within the design process that leads to benefit (as in Figure 3), the study of creativity within engineering design becomes the study of the generation of what can be thought of as benefit. Whether creativity has led to the overcoming of obstacles or has significantly improved product potential, its study within engineering design provides a context of benefit and a wealth of past research that can be explored. This perspective creates a structure for research; through a focus on creativity within engineering design, the array of associated literature creates a focus on the study of engineering design with an aim of creating benefit in engineering design output.

Within the domain of engineering design and beyond, creative behaviour has in general received considerable attention. For example, researchers have considered creativity within the co-evolutionary design process (Maher and de Silva Garza, 2006, Dorst and Cross, 2001, Cross, 2004a), creativity and design constraints (Stokes, 2007, Onarheim and Wiltschnig, 2010), creativity and expertise (Cross, 2004a, Goncher et al., 2009), and the relationships between creative and routine design (Brown, 1996, Dym, 1994, Gero, 2000). These are explored in more detail in Sections 4.2 to 4.4.

In a more specific sense however, study into creativity and engineering design has to date had a bias within the study of design process, focusing on the process as a whole and towards those stages of the process that are traditionally thought of as conducive to creative behaviour. While design is unequivocally considered a process that passes through many stages with considerable variation between them, creativity research has, to date, focussed on the study of the conceptual stages of design, or has not considered the role of design process and stage explicitly (see Figure 4). A small amount of work breaks this trend, such as Eckert et al. (2012), Motte et al. (2004b), Motte et al. (2004a), and Bender and Blessing (2004); but as has been noted by researchers (Matthiesen, 2011, Motte et al., 2004b), consideration of designer behaviour with the specific context of later-stage design is currently an under-developed subject. This gap forms the focus for the research within this work, and is further explored in Section 4.5.

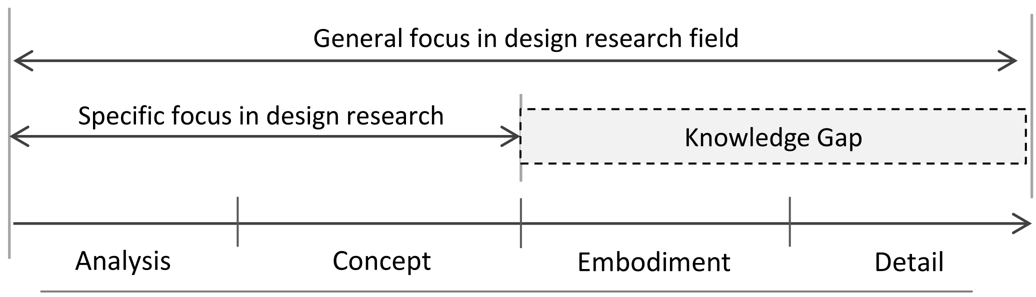


Figure 4: Knowledge gap in engineering design research

1.6 The Focus of Research: Later-stage Creative Design Behaviour

The focus and purpose of the work presented throughout this thesis is to address this knowledge gap – that of the behaviour of designers within the later stages of the engineering design process.

As will be discussed in Chapter 3, the later-stages of the design process are different to the early in many ways. For example, research has demonstrated the variation present in constraints as the design process progresses (Howard et al., 2011, McGinnis and Ullman, 1990), variation in goals and purpose of each design stage (Howard et al., 2008a), and the variation in tasks and activities that occur throughout the design process as seen in many process models (Pahl and Beitz, 1984, Pugh, 1990). As a result, it is neither sufficient to generalise research and understanding from early-stage research nor to assume that general research is also applicable when considering the later-stages alone.

1.6.1 The Research Aim

The rationale for the work completed in this thesis is that of providing an understanding on which future work can build. In order to develop effective and appropriate methods of designer support, it is first necessary to have a detailed understanding of the design situation and behaviour of the designer. Due to the lack of research into this subject as illustrated by the knowledge gap (Figure 4), there must be a focus on characterisation and description of the behaviour of designers in later-stage design; which in turn can be used for the eventual development methods of designer support.

The aim of this research is:

“TO CHARACTERISE THE CREATIVE BEHAVIOUR OF DESIGNERS WITHIN THE LATE-STAGE ENGINEERING DESIGN PROCESS”

1.6.2 Research Questions

This research aim contains two unique but intertwining aspects that must be considered, namely that of creative behaviour, and that of later-stage design. In addition to these is consideration of validity of results, the extent to which characterisations are applicable and useful in industry and across design situations, and hence the opportunities that results provide. This work therefore addresses the stated research aim through three distinct research questions:

1. What are the characteristics of creative behaviour in the engineering design process?

This question addresses the need for understanding of the manifestation and effect of creative behaviour within the engineering design process in general, in order to understand the intricacies of later-stage design. This research question is addressed by research objectives one and three.

2. How does creative behaviour manifest within the later-stage design process?

The question addresses the need for specific understanding of the appearance of creative behaviour in later-stage design, particularly as a distinct entity to early stages; and for understanding of the later-stages of the design process in general. The research question is addressed by research objectives two and three.

3. What are the opportunities for designer support in later-stage engineering design?

This question deals with the need for understanding of the implications of the appearance of creative behaviour in the reality of the design process, and hence of applicability of results and the opportunities that they suggest. Specifically looking at the later-stage of the engineering design process and the findings produced within the results and discussion of this thesis, this research question provides initial direction for the support of designers and hence improvement of process or output. This research question is addressed by research objectives three and four.

1.6.3 Research Objectives

To answer the research questions, which are multi-faceted in themselves, a series of formal research objectives have been formed. These are to:

Objective 1*: Identify the typical features of creative behaviour within design*

Objective 2*: Identify the typical features of the later-stage design process*

Objective 3*: Investigate the appearance and integration of creative behaviour within the later-stage design process*

Objective 4*: Develop understanding of the opportunities for improvement of creative behaviour within the later stages of the design process.*

1.6.4 Research Approach

To provide structure and clarity to the research approach and methodology, this work follows the now well-accepted Design Research Methodology (DRM) model of Blessing and Chakrabarti (2009). In its typical form, the research activity by DRM passes through a combination of descriptive and prescriptive stages by which the research goal is identified and addressed; as elaborated within Chapter 5. As performed in this work, the research activity completes highly comprehensive descriptive study (equivalent to DS-I in the DRM methodology), and does not complete the consequent PS-I and DS-II stages. This is due to the nature of the work as highly descriptive study of designer behaviour, forming characterisation rather than discrete support methods or tools. For the sake of clarity the entire DRM process is summarised here, while DRM as followed within this work is detailed in Chapter 5.

The first of these, the Research Clarification (RC) stage occurred through comprehensive study of the engineering design literature and that from related fields, with a particular focus on creativity, the structure of the design process, and the behaviour of engineering designers. The learnings from this stage were bolstered with a Descriptive Study (DS-I). DS-I included both an initial forming phase that occurred parallel to the RC, forming the analysis methods of the research proper, and a comprehensive descriptive study demonstrating validity of results and initial findings. This occurred through the use of engineers' logbooks (and hence is referred to in this work as *study one* or the *Logbook Study*), and studied the design process from the point of task analysis to the development of a proof-of-principle prototype.

Following this initial descriptive stage, a second study occurred with the goal of producing results that were highly focused on the areas of interest within the design process. This research involved a contrived design situation, chosen to mimic the real-life design process while stimulating designers to later-stage design tasks. Due to the lower commitment of involvement within this study, it could be applied both to participants in academia and in industry, providing a strong basis for comparison with DS-I and validation of results in a real-life context. Falling within this section of the methodology lies study two, consisting of the contrived study (referred to as *study two* or the *Observation Study*), and a detailed investigation of the quality of design solutions produced.

Finally, validation of results within industry was confirmed through a third descriptive study, with a purpose of confirming results within an industrial context, and providing realistic basis for the implications that said results hold. This study included observation of industrial designers in a laboratory study, in an industry setting, and is referred to as *study three* or the *Contextual* Study in this work.

1.7 Thesis Structure

This thesis follows a structure chosen to maintain consistency of subject between chapters, and so is split into four distinct sections (see Table 1). Elaboration of this structure, and particularly the methodological consideration of the project as a whole, is present in Chapter 5.

The initial section concerns literature and background, the formalisation of the research project and the research methodology. The second section concerns the attainment and presentation of results towards the primary aim of the work – characterisation of designer behaviour within later-stage design processes. For this reason, Chapters 6 and 7 contain the development of the framework for research and methodologies of the logbook and observation studies. The following two chapters are then able to present results from these studies, grouped by theme for consistency in understanding. The third section then provides methodology for the contextual studies and consequent results. This structure allows findings to be presented according to consistent theme, rather than study in which they are manifest, and hence prevents repetition. Cumulative discussion of all findings can then occur in the fourth section. The structure of the thesis is elaborated in more detail by Table 1 and Figure 5.

Table 1: The thesis structure, research questions, and objectives

Chapter	Description	Methodological Stage	Research questions	Research objectives
Section 1: Research Clarification Stage				
Chapter 2	Through literature review, detailed analysis of the state-of-the-art of the field of creativity.	Research Clarification	1	1
Chapter 3	Through literature review, detailed analysis of the process of engineering design.	Research Clarification	2	2
Chapter 4	Through literature review, detailed analysis of the traits of designer behaviour.	Research Clarification	1	1, 2
Chapter 5	Presentation of the research methodology, aims, questions and objectives.	--	--	--
Section 2: Presentation of Primary Findings				
Chapter 6	Development of the coding scheme and framework of analysis.	DS-I	--	--
Chapter 7	Presentation of the methodologies of studies one and two.	DS-I	--	--
Chapter 8	Presentation of results concerning creative behaviour and creative approach displayed by designers in studies one and two.	DS-I	1	1, 3
Chapter 9	Presentation of results concerning behaviour, comparison of behaviour between stages. Results taken from studies one and two.	DS-I	2	2, 3
Section 3: Presentation of Contextual Findings				
Chapter 10	Presentation of the methodology of study three. Presentation of results concerning the evaluation of results, and validity in context of industry and expert designers. Results taken from studies one, two and three.	DS-I	3	3, 4
Section 4: Discussion and Conclusion				
Chapter 11	Discussion of the findings from the research.	DS-I	1, 2, 3	1, 2, 3, 4
Chapter 12	Concluding statements	--		

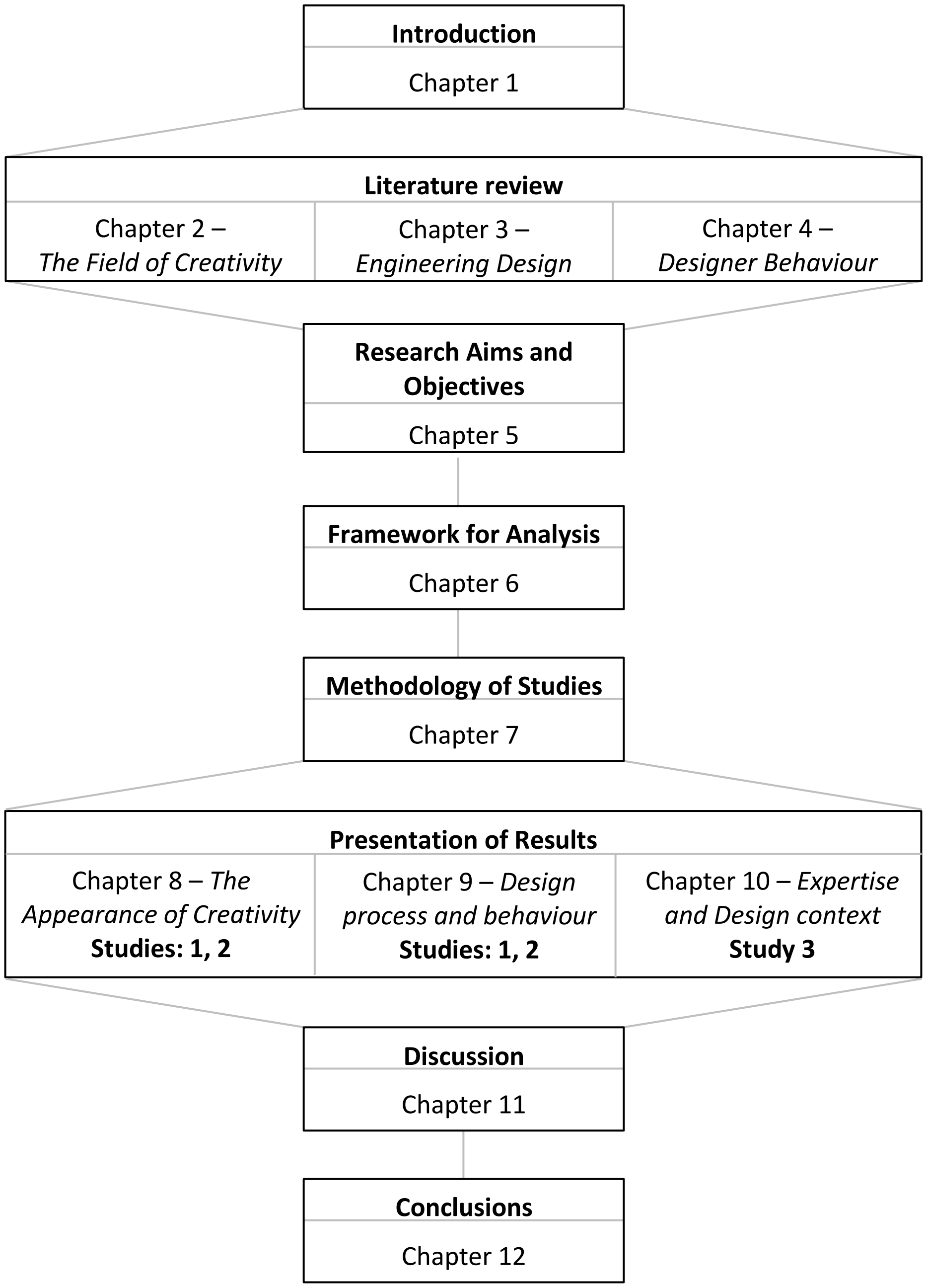


Figure 5: The structure of the thesis

Chapter 2: The Study of Creativity

In modern times, the study of creativity is rightly given much importance across many different contexts and from many different perspectives; and has led to many insights and gains across both academic and non-academic subjects. It is perhaps then surprising that the study of creativity in and of itself is in relative terms quite a young field, with the vast majority of work completed in only the last fifty or so years.

The study of creativity began in force within the field of cognitive psychology, mainly as a result of an address by Guilford (1950), clearly admonishing the neglect he felt the subject had received up to that point. This encouraged a quick response, with a wide variety of continuing literature published from that point up to the present day (see Anderson (1959), Rhodes (1961), Amabile (1982b), Sternberg (1999), Kaufman and Sternberg (2010)).

As a result the study of creativity is now imbued with vital importance across many fields, and is performed from a multitude of perspectives from science (see Bohm and Peat, 2010), to art (Stokes, 2006) and business (Bilton, 2007). Particularly in the space of design engineering, creativity is recognised as a vital (if complex) component within the design process, and has received the attention of a growing number of researchers over the past few decades.

In order to understand why the study of creativity has grown into a topic of great importance and what can be gained from such research, it is first necessary to understand *what* creativity is, *how* it manifests, and the outputs that it can generate. Answering these questions is no easy task, as has been discovered by many, is often marred by complexity and confusion, and has in many cases still not led to consensus (Chakrabarti, 2006).

It is the aim of this chapter to present an overview of the field of creativity and its development, and to place the perspective and context from which this work is completed.

2.1 The Difficulty of Definition

It might be expected that the first stage in the study of creativity is to identify an explicit definition on which work can be based. Indeed, many definitions have been proposed as the field has developed (Couger, 1990). However, partly due to the many facets of creativity that will be described within this section and partly due to the variety of perspectives from which study is completed, a distinct lack of consensus still exists (Chakrabarti, 2006).

2.1.1 The Four Pillars of Creativity

One source of this vagueness reflects that in the human mind creativity can be seen in many different forms, but these forms are not necessarily consistent or intuitively comparable. Many can point to a an object in front of them and state features that they believe denotes it as creative, but difficulty arises when attempting to identify features in the process that created the object, which can clearly also be described as creative in its own right; or in the person that created it and environment in which creativity arose.

In his analysis of the state of the then-young field of creativity, Rhodes (1961) noted that creativity as a whole is not suited to subdivision. He identified four key areas to which creativity is understood to apply, stating that only through consideration of all can creativity be understood. Termed the "*four pillars of creativity*" (Figure 6), these include the *creative person*, the *creative process*, the *creative context*, and the *creative product*. Throughout creativity research these four pillars have proven valuable, providing structure, context and comparability for study.

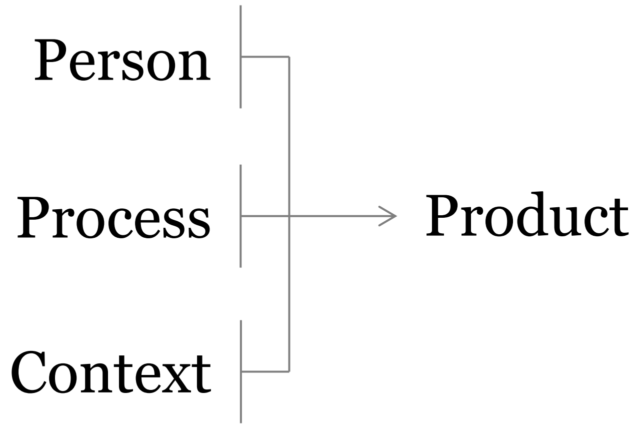


Figure 6: The four pillars of creativity, adapted from Samuel and Jablokow (2011)

By this framework, creativity can be considered as an amalgamation of characteristics that individually relate to one of the pillars, solving the contradictions of different traits appearing in different contexts. Without understanding of any one of the pillars understanding of creativity is incomplete; while consideration in the context of each produces focused and valid research.

Also by this framework then, "creativity" as a term can be defined only as a high level descriptor of a field, specifically as an amalgamation of the factors that influence the development of a creative output. Each individual pillar is important to the understanding of creativity, and yet each pillar is distinct in its own subject matter. Any one pillar is insufficient to act as defining of any other, and all are required for understanding to be complete. For this reason, there is no low-level definition of "creativity" that is meaningful in all situations. For example, creativity of a product can be considered as evidenced through each product's individual characteristics (namely originality, appropriateness, and surprise; Section 2.2). Creativity of a person can be considered as an ability to produce a creative product, typically manifest through personality traits and knowledge (see Section 2.3). Creativity of a process can be considered the designer activities by which a creative solution comes to be, identified in classical literature by incubation and illumination (see Section 2.4). Creativity is here then used to describe a body of research, rather than a concept in its own right.

Due to this broad variation in meaning, creativity at a low level cannot be usefully stated without a subject categorised within the four pillars (as occurs within this work) or some other construct. The subject of what is being determined as creative in each individual case of use of the term determines the context of what it means in that case – when referring to a product, the definition of a creative product is applicable; when referring to a person, the definition of a creative person is applicable. It is for this reason that throughout this thesis the term creativity is not used without a subject that is being considered creative, except where it is used to refer to the field as a whole. "Creativity" as a term is considered a broad descriptor of a number of subjects, each of which is independent in its form but all of which are needed to understand the field of creativity as a whole. As a result, there is no definition of creativity capable of singularly defining all of its facets in a consistently applicable manner; it is only through sub-division that creativity can usefully be understood.

It is to this end that this chapter occurs, studying each of the four pillars in detail in order to form a detailed understanding of creativity as a research field and a whole; one that is broad in scope and considerate of each facet that influences the overall creativity of the subject. The culmination of the chapter is then an understanding of creativity as a broader concept, and the role and form of each pillar within it. As a result, it is possible to understand the nature of creativity and its appearance within engineering design without discrete low-level definition; forming an understanding of the vital underlying and consistent concepts that the four pillars of creativity describe.

2.1.2 The Four Pillars within Engineering

The study of creativity is well-recognised across fields, such as art (see Stokes, 2007), psychology (Amabile, 1996, Boden, 2004), and engineering design (see Gero, 1996, Howard et al., 2008a), while creativity itself is to be considered as valuable in many more (Sternberg and Lubart, 1999). However, due to differences in areas such as process strategy (Lawson, 2006) and problem structure in design (Simon, 1973, Dorst, 2006), engineering must be studied explicitly. While an abundance of relevant research can be drawn from cross-disciplinary sources, the individualities of engineering require all study to be carefully framed in order to maintain appropriateness and applicability.

The goal of the following section is to present a detailed understanding of state of the field of creativity theory and research within the context of application to engineering design, and more specifically from the perspective that is taken within this work.

2.2 The Creative Product

Given the solution-focused nature of engineers and engineering in general (Pahl and Beitz, 1984, Lawson, 2006) it is perhaps not surprising that much research considering creativity places focus on the definition of a creative product; those characteristics that denote a product as more (or less) creative than its peers.

First in developing an understanding of a creative product, is to clarify to what the term *product* itself can apply. In his original distinction of product as a pillar of creativity, Rhodes (1961) places a hierarchy between ideas and the inventions that they produce. That theories such as that of electromagnetism have allowed the development of countless innovations from motors to lasers, Rhodes claims, places them as of higher order of novelty than the inventions that they inspire. In other words, an idea that spawns much "newness" is of higher classification that the newness that is spawned. This perspective perhaps lacks detail – for example, that an idea is considered of higher newness due to its use actually implies that some element of usefulness is actually necessary in the definition of creativity, and it is this element that differentiates between idea and invention, rather than "newness". However, it does underline an important property of a product – there is no need to be physical to be considered creative, and indeed a non-physical product may be of equal or higher value to a physical one. This work then takes the view that at any stage and at any time the results or goal of a designers work form their product, be it an idea in a brainstorm, a few words in a brief, a virtual or physical design, a tooling sequence, or a management process.

While the hierarchy of newness of Rhodes creative products may be valid in a cross-disciplinary sense, within engineering design the stricter adherence to design as solving a specific problem reduces applicability. Due to the lack of method for determining creative "newness" and the lack of distinction between "newness" and some element of usefulness, other, more developed criteria and assessment methods are needed.

Concerning the products of engineering design, which may range from a system, to software, to a physical artefact, numerous terms have been used to act as the defining characteristics of those which are creative (Couger, 1990). A grouping and analysis of these terms was conducted by Howard et al. (2008a), who noted that all terms could be grouped under the headings of *appropriateness*, *originality*, and *unobviousness*. Examples of these terms can be found across literature, as shown in Table 2.

Here, although categorisation of terms of each researcher is possible into the given categories, it is important to note that those used by the original researcher are not always identical. For example, within the *appropriateness* category, terms from literature included valuable (Hayes, 1989, Rhodes, 1961), appropriate (Sternberg and Lubart, 1999) and useful (Thompson and Lordan, 1999, Sarkar and Chakrabarti, 2011); terms within the *originality* category included novel (Chakrabarti, 2006) and original (Howard et al., 2006); while terms within the *surprise* category included surprise (Bruner, 1967), unexpected (Gero, 1996) and unobvious (Howard et al., 2006).

Table 2: Definitions of the creative product

	Appropriateness	Originality	Surprise
Psychological Research	(Plucker and Beghetto, 2004)	(Runco, 2004)	(Sternberg and Lubart, 1999)
	(Sternberg and Lubart, 1999)	(Sternberg and Lubart, 1999)	(Boden, 1994)
	(Amabile, 1996)	(Amabile, 1996)	(Bruner, 1967)
	(Hayes, 1989)	(Boden, 1994)	
		(Eysenck, 1994)	
		(Hayes, 1989)	
		(Rhodes, 1961)	
Engineering Research	(Howard et al., 2008a)	(Howard et al., 2008a)	(Brown, 2012)
	(Howard et al., 2006)	(Chakrabarti, 2006)	(Howard et al., 2008a)
	(Kryssanov et al., 2001)	(Ward et al., 2004)	(Shah et al., 2003)
	(Thompson and Lordan, 1999)	(Shah et al., 2003)	(Macedo and Cardoso, 2002)
	(Cross, 1997)	(Kryssanov et al., 2001)	(Gero, 1996)
		(Thompson and Lordan, 1999)	

The category terms chosen, however, do reflect the intention of each. While value, usefulness, and appropriateness do not have identical meanings, all reference the need for a creative product to be of quality, to be better than alternatives. Both originality and novelty reference the importance of newness – of a product that has not previously existed in its current form. Surprise, unexpectedness and unobvious perhaps also imply newness, but with the caveat that the newness should not be a standard, expected progression of past designs or understanding.

From these terms the following definitions are formed, and serve as the defining elements of the creative product throughout this work:

Appropriate The degree to which the product output is of suitable quality as a method of completion of its desired function.

Originality The degree to which a product solution is previously unknown to its individual designer, the domain in which it will exist, or society as a whole.

Surprise The degree to which a product solution is unexpected to its individual designer, the domain in which it will exist, or society as a whole.

2.2.1 The Measurement of Creative Products

For many, it would be of great benefit to be able to determine the creative level of their products - i.e. robustly and relatively assess the extent to which their products are determined as creative. Associating creativity with desired characteristics of a product, those with higher creativity are also those that are more desirable for the company, and hence their judgement at an early stage may prove a decision-maker for concepts to undergo further development.

There are several examples of the development of metrics for some common aspect of creativity within literature, both described formally or implied informally. For example, Sarkar and Chakrabarti (2011) define creativity as a combination of importance and usefulness, and present metrics based on procedural but often subjective judgements of a certain product in comparison to its competitors or nearest equivalents. Shah et al. (2003), in his metrics for ideation effectiveness, provides methods for judgement of novelty through comparison of major function carriers between concepts with those that occur less often; a process that has been utilised by others (Agogue et al., 2011, Lopez-Mesa and Vidal, 2006).

Of the terms presented in Section 2.2, *appropriateness* is the simplest to determine. Taking the definition of quality to refer to the completion by a product of a series of goals – termed *dimensions of quality* (Garvin, 1987), with categories such as performance, features, reliability and cost (Kolarik, 1995, Garvin, 1987) – appropriateness as defined can be measured through many well-accepted methods. The inclusion of *appropriateness* in definition of creativity then refers to the more creative product as being of higher quality than its peers, but with respect to the brief and specification that describe the problem. For example, a product of excellent performance may be deemed of high quality, but of lower appropriate quality if the higher performance also raises cost to unfeasible levels. Suitable techniques for quality assessment then include methods such as QFD (Kolarik, 1995), decision tables (Pahl and Beitz, 1984) or the evaluation matrix of Pugh (1990).

Both *originality* and *surprise* are more difficult to measure. Some formalised methods of judgement of the former exist, generally relating to assessing different aspects of a design against an equivalent, existing design (thereby providing a relative value). Frequently however, the category selection or assessment procedures are somewhat subjective in nature and rely on the opinions of evaluators, and hence are liable to change depending on (for example) context or evaluator experience. Although guided by rules and procedure, such methods are to some point based on assessment through expert opinion and hence require care in use.

As a term within the definition of creativity, *surprise* has only recently received attention, primarily in the field of computational assessment of products, such as Macedo and Cardoso (2002). Within broader engineering design literature, although mention has been made to a characteristic of unexpectedness or surprise (Howard et al., 2008a, Gero, 1996, Lopez-Mesa and Vidal, 2006), no applicable methods of evaluation have been found. Surprise is, however, described as judgement of a product as breaking existing expectations of its form (Brown, 2012) by taking a form that cannot be deduced from knowledge of the existing design space. Here, as with originality, there is judgement of an evaluator required for assessment, who naturally would base their interpretation of surprise on their own personal background, experience and knowledge (Brown, 2012).

2.2.2 Context Dependency and Expert Judgement

As mentioned in terms of *originality* and *surprise*, a key pattern within these methods of assessment (and one that continues through much of creativity research) is that of assessment through opinion of experts (referred to as a Consensual Assessment Technique (CAT)(Amabile, 1996)). Ideally, it would be beneficial to provide robust, algorithmic methods of assessment. However, this is prevented through an inherent context-sensitivity that stretches throughout the study of creativity.

As discussed by Boden (2004), the concept of originality is relative to the person or society in which it is judged. In her terminology, *p-level* novelty refers to novelty in the eyes of the creator – a previously unknown artefact in the case of engineering. *H-level* novelty refers to novelty in the eyes of history – an artefact that previously did not exist at all. In addition, others have added a third category of *S-level* – an artefact that is novel to the *society* or field in which it now exists (Suwa et al., 2000). This implies that creativity is in some manner reliant on the interpretation of an observer and that said interpretation is to some extent based on observer experience.

This suggests a context sensitivity that is widely accepted in the field (Chakrabarti and Khadilkar, 2003, Shalley and Gilson, 2004, Amabile, 1996, Lubart and Getz, 1997). What is creative to one party may not be considered so by another. For example, while an engineer may develop what they would term a non-creative product; through a lack of domain-specific knowledge their customer may view the product as both original and appropriate - hence as highly creative. Conversely, while an engineer might produce an unusual solution through cross-field exploration and development, there is no guarantee that the customer will recognise the unusual characteristics. To them, the solution may still be considered non-creative.

Rigid, algorithmic methods of assessment do not compensate for these complications, and can therefore introduce error. It is hence important in any form of assessment method that elements of judgement within context are allowed. Sarkar and Chakrabarti (2011), although their methods provide significant structure, require expert interpretation of the usefulness and importance of a product. Shah et al. (2003) require definition of the categories of assessment and weighting system by experts in their metric of novelty. Torrance (2008) (within the domain of psychology) interprets a number of manifest criteria judged by human coders to find traits of creativity leading to assessment of a person's creative level. In reality this consideration of expert opinion is the norm, few objective methods of creative evaluation exist (Amabile, 1996).

2.2.3 The Creative Product within this Work

Intuitively, the assessment of the creative product seems one route to the study of process – those that result in a creative output could be expected to contain creative behaviour. However, due to the role of context sensitivity and interpretation of a judge, this route is made complex.

The significant difficulty in the study of creative products stems from a lack of feasible objectivity. Due to vast differences in experience and interpretation between societies, domains and individual people, there are differences in what is and is not deemed to be creative, and even the categories by which assessment should occur. For the purpose of assessing creativity within process and behaviour of engineering designers (as occurs within this work), it is therefore very difficult to make judgements based on the product of their work; inherent variation in what is and what is not judged as creative will greatly influence processes that are identified as creative.

Further, the question of to whom the product is judged as creative is important for research. It must be considered that some products may be produced through identical processes, and yet one is judged creative due to the experience of the customer base and their general interpretation. In such cases, there is an argument to be made that the judgement of the output as creative is a result of the market, advertising, and other designer-independent forces, rather than as a result of the design process. These cases would accordingly fall out of scope of the work, as there is no example of creative behaviour in the production of the output. Although a potential area for study, such a topic would not lie in the field of engineering design research.

There are clearly then issues relating to the identification of creative processes through the outputs that they produce; ambiguity exists in terms of whether a creative output is always a result of a creative design process, as it does in the necessity of a creative process to result in a creative output. To maintain applicability in as broad a scope as possible, this work proceeds by analysis of the creative process and person directly, rather than through identification of a creative product and subsequent analysis of the process that led to it. As a process of some description is necessary for any product to come to exist, this provides a focus for research that is consistently present between design situations and products, and so is widely applicable. Further, this approach encourages study of all processes regardless of whether they result in a creative output, which through comparison between different processes may provide deeper understanding into the relationship between the two.

2.3 The Creative Person

A constant throughout the design process is that of the presence of a designer, usually one who is human (although the field of computer-based design is steadily growing). Given this fact, it is vital in research to consider the role that the person plays throughout the process, and to do this it is also vital to understand the person themselves.

Within the field of creativity there has been much research into the creative person and the characteristics that they often possess. The understanding generated then becomes a basis for future research into creative behaviour and design processes, training of less-experienced designers, and knowledge from which computer-based design can be developed. This section will discuss links that have been researched between creativity and traits of people.

2.3.1 Creativity and Intelligence

While there are some links between creativity and intelligence, they are neither essential nor causal to one another. From a psychometric view, there are a number of points to be made regarding the relationship between the two, as set out by Sternberg (2011).

Creativity, as tested by a variety of measures, has shown that creative people will demonstrate a higher average IQ than the average population. Due to the fact that the converse is not true (intelligent people are not always creative, noted by Getzels and Jackson (1962)), other theories have emerged; such as the three ring model of Renzulli (1986), which treats creativity as in an overlapping set with above-average ability (judged in this case through intelligence) and task commitment. Ability in each can then lead to giftedness in each, but while some form of relationship may exist there is no necessity for giftedness to appear in all. As such an intelligent person should not be treated as creative by rote, and nor should a truly creative person be expected to be exceptional in intelligence.

Above an IQ of approximately 120 the value becomes less relevant to the creativity of the person. As summarised by Barron (1963); below a value of 120 a positive correlation of around 0.40 exists, but beyond the effect of intelligence becomes negligible and the stylistic and motivational factors of personality become the deciding variables. Creativity and intelligence are therefore, in general, not correlated. Research into the correlation between creativity and intelligence has been shown to vary only from slightly negative to slightly positive (Barron and Harrington, 1981, Getzels and Jackson, 1962, Sternberg and O'Hara, 1999).

For the purpose of engineering design research, intelligence must therefore not be thought of as an important factor. On average, the IQ of engineers is above the threshold of 120 (Eysenck, 1973), and so no intelligence-based variation in creativity can be expected within the engineering community alone. Indeed, the evidence that intelligent people are not by rote creative claims that differing levels of creativity are to be expected, to the extent that some engineers will innately tend to the non-creative solution. This is not to be thought of as a negative trait, as it is entirely feasible that in many situations neither a creative process nor creative product are desirable.

Despite the substantial work into creativity and intelligence, complete consensus has not been made on how the relationship may form, should it truly exist at all.

2.3.2 Creativity, Knowledge and Experience

Within large parts of the research community there is little doubt that knowledge, and perhaps more precisely experience, are vital traits of the creative person (Cropley, 2006, Christiaans and Venselaar, 2005).

Evidence from the study of eminent individuals who display high creativity has shown that it takes years to reach the point of creative productivity (Hayes, 1989, Ericsson et al., 1993); during which the person will immerse themselves in the field, gathering both the relevant knowledge and experience needed to produce creative results.

Interestingly, similar conclusions can be drawn from study into the levels of education of highly creative people (Simonton, 1984); in which the average level of education has been found to be a Bachelor’s degree. The important statement here is that of formal training. Although deliberate training designed to improve skills will produce maximal results and overcome performance-based plateaus (Ericsson et al., 1993), simple immersion in a field will also (to some extent) increase performance (Ericsson and Lehmann, 1996).

As is discussed in Section 4.2, the role of expertise and expert behaviour is important and well-studied within design research. Through differences such as those in design process and approach (Atman et al., 1999, Ahmed et al., 2003) and problem-solution strategy (Cross, 2004a, Ho, 2001), experts are thought to produce higher quality designs (one requirement for a more creative product).

The production of creative solutions can then be considered a skill that is learnt, rather than an innate talent. Through the process that they complete, experts are consistently able to produce “better” solutions than their novice counterparts. This suggests the importance of studying the process followed by the experts in comparison to the novice in order to identify the defining and useful features; a subject that is covered in detail throughout Chapter 4.

2.3.3 Creativity and Personality

Beyond their knowledge and intelligence, a person’s personality ties to their overall creativity. In an argument that perhaps pulls towards the contrasts between nature and nurture, differences arise between the characteristics of creative people dependent on field.

In a detailed literature review by Feist (1999), some basic similarities and differences were distinguished between those who are creative in art, and those who are creative in science. First, creative people tend to share several characteristics independent of field. They will be open to new experiences, less conventional, confident, driven, ambitious and impulsive. Second, while creative artists are less emotionally stable and accepting of group norms, creative scientists are more conscientious. Third, longitudinal study of adolescents growing through to adults have shown that creative personality is stable (Feist, 1999) – the creative characteristics present at a young age are also present when older.

In addition to implying links between creativity and personality, these findings propose that different personalities are capable of creativity. Linking to the work of others that suggest different styles by which designers are creative (Kirton, 1976), such individual differences are to be expected. Certain personality traits may imply creative ability, but these traits are not necessarily consistent across fields, do not imply extent of creative ability, nor require that all people are creative in the same way.

Research must then not generalise. In order to be applicable and valid, the study of creative people and their processes must work on a person-by-person basis, and value the role of individual difference.

2.3.4 Creativity and Motivation

Drive and ambition are often seen as vital in the creative person; the motivation that pushes them beyond the "routine" and into the extraordinary (Collins and Amabile, 1999, Prabhu et al., 2008).

Literature has identified two forms of motivation, intrinsic and extrinsic (Amabile, 1982a); the first to complete a task for its own sake, the second for the sake of some external goal or requirement.

Intrinsic motivation is considered positive; a fundamental desire within the person to proceed and succeed will encourage a creative outcome, in which the positive experiences gained from the exercise spur desire to complete it well (Amabile, 1996).

Extrinsic motivation is seen as more variable. Some have demonstrated that completing a task for an external goal can instil enthusiasm towards the task itself (thereby encouraging intrinsic motivation) (Ryan and Deci, 2000, Eisenberger and Shanock, 2003), and that the provision of explicit, difficult goals concerning both creativity and quality will increase the appearance of each in output (Shalley, 1991). Others have demonstrated the converse effect, that extrinsic motivation such as the knowledge that work will be evaluated will decrease creativity in results (Amabile, 1996).

Possible reconciliation of this conflict lies in the relationship between intrinsic and extrinsic motivation within a person, and the form that the extrinsic motivation takes. In cases where the extrinsic motivator is viewed as a helpful or informative influence on the process, creativity will increase. When viewed as a controlling or incompatible with intrinsic motivation, creativity will decrease (Collins and Amabile, 1999). In the former, the extrinsic motivator (such as a set of guidelines on which the design will be based) enables and supports the intrinsic motivation that the designer may hold. In the latter, the extrinsic motivator (such as a constraint on what it allowed), inhibits the designer and prevents progress.

Again, such thinking requires acknowledgement of individual difference in the production (and study) of creativity. Whether a designer is intrinsically motivated to complete a task is highly dependent on themselves and their enjoyment of the subject, as is whether their sources of extrinsic motivation are judged to be encouraging or inhibitory.

2.3.5 Recognising Creativity in the Person

A common trend in each category described so far has been individual difference and variability. The creative person is intelligent, but the intelligent person is not always creative. The creative person is knowledgeable, but does not always need to draw on this knowledge for creativity.

The creative person is intrinsically motivated, but motivation is dependent on circumstance and preference. While all of these are features of the creative person, none can be used objectively as a comparable measure of their creativity. To comparatively assess creativity between people, the measure must study traits that are consistent across the creative (and non-creative) population regardless of situation, person, their experience, their knowledge or their motivation.

Amongst the many measures of creativity that have been developed (see Kirton, 1976, Guilford, 1956, Getzels and Jackson, 1962, Torrance, 2008), the most popular are perhaps the Torrance Tests of Creative Thinking (TTCT)(Torrance, 2008). These tests have received both significant scrutiny and support (Kim, 2006, Cramond et al., 2005, Lissitz and Willhoft, 1985), and are now regularly employed in a wide variety of fields. They use a series of figural and verbal tests to measure five subscales, which are then used to calculate a person's *creativity index*. The TTCT themselves were developed by Torrance and his associates over a period of 25 years, and are specifically designed to use activities that reflect different types of thinking modes within the creative thinking process (Torrance, 2008). It is then the proposal of the TTCT tests that five subscales denote the creativity of a person, outlined below:

Fluency

Creative fluency refers to the number of ideas that a person may generate. There is a common trend of understanding within creativity research that a higher number of generated ideas will lead to higher creativity in output (Shah et al., 2003). Justification for such is however incomplete, with some contrary evidence that too high a quantity will lead to a decrease in output quality (Fricke, 1996). An ability to produce a large number of ideas is perhaps better seen as an indicator of good flexibility in design or an ability to resist fixation on solutions, both of which are considered important characteristics of the creative person (Ward, 1994, Jansson and Smith, 1991).

Originality

Originality in solutions as a characteristic of creativity represents the ability of a person to produce ideas that are uncommon or unusual. Although it must be considered to whom the solution can be considered creative (Boden, 2004), there is thought that the ability to produce a high number of ideas that others would not is closely tied to creativity (Hayes, 1989, Runco and Charles, 1993). Considering the parallel appearance of originality as a defining characteristic of the creative product (Howard et al., 2008a), its inclusion as an ability of a person is logical.

Elaboration

In order to be creative, you must be able to produce ideas that are within context of the problem and are in sufficient detail to see feasibility and potential issues. Elaboration refers to the ability to develop or embellish an idea (Carson, 1999), following the assumption that displaying understanding of detail and context are indicators of creative ability (Torrance, 2008).

Abstractness of Titles

As a measure of the level of abstract thought of a person, this factor reflects the ability to think in terms that are not immediately present within the situation, in which the designer raises their interpretation to a higher, less concrete level. It also reflects the ability to think in a divergent fashion, as advocated by Guilford (1956). Within the literature, this trait has been seen in the comparison between experts and novices (Motte et al., 2004a), in which experts draw analogies of a far more abstract form; the influence on abstraction of analogy on creativity of a solution

(Chan et al., 2011) and the study of exceptional designers (Cross, 2004a), who form their problem in a fundamental manner that abstracts away from potential preconceived notions of the solution.

Resistance to Premature Closing

Based on the assumption that with time comes a higher probability of the "creative leap" (Torrance, 2008), resistance to premature closing reflects the openness of a person, and the potential willingness to consider and accept concepts beyond those typically produced. It is to some extent mirrored by the role of flexibility as an indicator of creative ability (Hayes, 1989, Guilford, 1968, Helson and Crutchfield, 1970), in which a willingness to consider many different (and even conflicting) factors during the design process will lead to a more creative solution.

Of note within these characteristics is their evidence-based approach to measurement. While the TTCTs have demonstrated success and built a wide base of support, they cannot be said to identify the creative qualities of people, but rather to identify that creative qualities are likely present within a person based on their individual output. Thus these categories, in a similar manner to traits such as intelligence and knowledge, cannot be said to be entirely comprehensive or even strictly necessary; perhaps accounting for the more neutral results that some studies have found relating between the TTCTs and creativity. The point is well made by Kim (2006); the TTCT and hence categories of assessment have formed an important part of research into creativity assessment, but due to the multi-dimensional nature of creativity, and as stated by Torrance (Treffinger, 1985), measurement should not be based on the TTCT alone.

2.3.6 Creative Style

The fundamental premise of the measurement of creative level is that there is an appreciable and objective set of criteria that describes the creative abilities of a person. The importance of the role of individual difference makes this a debatable concept.

As suggested by differing creative personalities (Section 2.3), there is an argument to be made concerning the manner in which people are creative, termed creative *style*. This is not illogical - the array of individual difference throughout the study of creativity suggests that difference may also exist in the way in which a designer performs creative behaviour.

Consequently, determination of creative style has been a subject for research. One proposed example is the creative problem-solving profile (CPSP) (Basadur and Gelade, 2003); which describes an individuals' creative style through their preferences for certain types of knowledge manipulation, matched to stages of the creative design process. By their assumption, strong preference for one or more type indicates a creative style.

A more process-independent measure is that of Kirton (1976), who developed the Kirton Adaption-Innovation (KAI) scale. Within, persons are placed on a spectrum based on their innate preference to "do things better", versus to "do things differently". The scale states that, at the extremes, people are either of the type who will work well within existing systems and principles to produce excellent results (termed an *adaptor*), or will be of the type that frequently breaks rules and discover alternative solutions outside of convention (termed an *innovator*), see Table 3. In reality, the vast majority of people will be placed at some intermediate point within the spectrum.

Table 3: A selection of behavioural descriptions of adaptors and innovators (Kirton, 1976)

Adaptor	Innovator
Characterised by precision, reliability, efficiency, methodicalness, prudence, discipline, conformity.	Seen as undisciplined, thinking tangentially, approaching tasks from unsuspected angles.
Concerned with resolving problems rather than finding them.	Could be said to discover problems and discover avenues of solution.
Seeks solutions to problems in tried and tested ways.	Queries problems' concomitant assumptions; manipulates problems.
Reduces problems by improvement and greater efficiency, with maximum of continuity and stability.	Is catalyst to settled groups, irreverent of their consensual views; seen as abrasive, creating dissonance.
Seen as sound, conforming, safe, and dependable.	Seen as unsound, impractical; often shocks his opposite.

The relationship between Kirton's styles and creativity is somewhat complex. Although he proposes that the two can be classed as creative styles, with no difference in personal creative level inherent between the adaptor and the innovator (Kirton, 1978), others have found some correlation. These place the innovator as the more creative (Goldsmith and Matherly, 1987, Torrance, 1980, Isaksen and Puccio, 1988), a possibility that Kirton states is in line with much thinking on creativity (Kirton, 1976).

On the KAI scale then, the innovator is seen as the person who demonstrates a higher creative level through their actions or behaviour, and hence is more likely to produce a creative result. However, as contested by Kirton, the method of producing a creative result may vary according to personality and behavioural preference. It is equally valid for a designer to be creative through development according to understood and relevant paradigms (the *adaptive* method) or through development and discovery of new solution paradigms (the *innovative* method). Such considerations need to be made in any study and analysis; not only may a designer be more or less creative than another, they may also to be equally creative by a different approach. Such thinking on creative style is of great interest within this work, and will be developed within later chapters.

Viewed as particularly important within this work, it is the process independence of the KAI scale that enables its usefulness. As is discussed within Chapter 6, throughout the design process there is a variation in the tasks and activities that will be completed by each designer. Although the creative process can be considered separately to the procedure by which a product is developed, description of style through relation to the creative process (the method followed by CPSP) places an assumption that each separate stage of the design process is equally conducive to each separate stage of the creative process. While this may or may not be true, instead of making this assumption the KAI test measures based on personality traits and patterns of behaviour (which have been demonstrated to affect creativity), as such relying solely on the designer under analysis and their personal style. Given that this work focuses on creativity throughout the design process, interpretation of creative style that is process-neutral allows both generalisation and comparison of results across design stages.

2.3.7 The Role of the Creative Person within this Work

The most important observation in literature of the creative person is in individual difference. Different designers will display different "levels" of creativity than others, will be creative in different ways and will be creative in different situations. When the goal of research is to fully understand the traits that manifest in a creative person, this creates a complex web that must be navigated.

In this work, however, it provides some structure for study. In all cases of interest, it is a designer who is being creative. This designer may be creative in a number of different ways dependent on personality and motivation, which may be closely inter-related. There are some methods to determine the creative abilities of a designer (giving their creative level), although these are not individually exhaustive. What is clear, however, is that designers are more creative with experience, suggesting both that creative ability is a learned trait (at least in part), and that creative output is dependent on the creative ability displayed.

For this work then, which aims to study creative behaviour in later-stage engineering design processes, this literature provides some structure. Study must consider designers individually, in order to capture individual difference and style. Understanding of the difference between novice and expert designers may demonstrate the process characteristics that encourage the production of a creative output. Creative behaviour within a process can be influenced, for example through affecting a designer's motivation. These guidelines inform the framework developed for research, presented in Chapter 6.

2.4 The Creative Process

Within the context of the four pillars of Rhodes (1961), the creative process refers to stages or steps by which creativity comes about, in terms of actions of a designer or their thinking processes. Particularly in relation to the creative product, some care must be taken when considering the creative process. As an entity, the process by which an output is produced is distinct from the output itself; one is a sequence of activities, explicitly stated or not, and the other is a tangible result or artefact.

A creative process may therefore be interpreted in two ways. The former describes a creative process purely as a sequence of steps from which a creative product results. Study here (and within the context of this work) then concerns the hypothesis that traits or patterns of behaviour will consistently appear in processes that produce a creative result. The latter describes a creative process as creative in-and-of itself. This interpretation implies inherent creativity in a process, and so describing the process itself as matching the definition of creative product presented in Section 2.2.

As will be discussed, literature on the creative process concerns mainly the former of these interpretations. However, the purpose of noting at this point is to frame what is viewed as important within the study of creative process. The goal of engineering design is to produce an output as solution to a specific problem. Creativity is viewed as an enabler to the study of this goal; due to the definition of creative product, that which is more creative is also that which better solves the initial problem. The study of the creative process is therefore the study of that which leads to this superior solution – the sequence of activities that lead to the result and the patterns of behaviour through which these activities are completed.

Whether the creative process can be defined as a creative product in itself is then of lower consequence. Interest lies in how the "better" solutions are produced and whether their production can be encouraged, and hence the behaviour by which production occurs. Creative behaviour within this work refers to behaviour in this sense, not as something that can necessarily be interpreted as creative in its own right, but as something that will likely encourage a creative product.

Following this thinking, it is necessary to define several terms in the context of this work and according to the perspective on the creative process that is applied (Table 4). Note that the definition for creative behaviour is here presented in general terms and is elaborated in Table 6, while behaviour is defined formally in Section 4.1.

Table 4: Definitions of terms relating to the creative process

	Definition
Creative Process	A term describing the overall sequence of steps by which a product that is judged to be creative comes to exist.
Creative Behaviour	The manner in which a designer completes individual tasks or activities within a creative process, that enables a creative product to be produced.
Creative Ability	The traits or characteristics of a designer that enable them to complete creative behaviour.
Creative Approach	The manner in which a designer completes creative behaviour.

These terms hold some assumptions. First, any process that produces a creative product is by definition a creative process. Second, in order for a creative process to occur, a designer must complete some form of creative behaviour. Third, creative behaviour as displayed by a designer is enabled through their creative abilities, and will occur according to their creative approach. The former of these is dependent on such factors as skill and experience, the later on personality and motivation; although there is likely a significant inter-relationship between the two. It is worth noting therefore that this work does not assume that creative behaviour will result in a creative product (and hence a creative process), only that the designer will complete behaviour that has potential to do so. Similarly, the creative abilities of a designer do not force or guarantee creative behaviour. This de-coupling of creative behaviour and creative product is important for research, as it allows processes of designers to be compared in a product neutral sense and considers that output can be very different even when process is similar, and so allows a more subtle analysis of the affect and influence that lead to a creative process.

2.4.1 The Classical Creative Process

Classically, the creative process has been described by Wallas (1926) as occurring through four stages. These emphasise both the importance of developing a strong understanding of the problem and also of a period of reflection through which a creative solution can develop.

- Preparation, in which the problem is formulated and understood.
- Incubation, in which the problem is not consciously thought about.
- Illumination, in which a sudden appearance of a solution is formed.
- Verification, in which the validity of the idea is tested, and it is brought to an exact form.

Within this process, the critical point is the appearance of a creative leap, referring to the sudden elucidation of a creative idea following a significant period of work. Examples of such events are frequent within literature and description, with typically cited examples including the Eureka moment of Archimedes, or the descriptions of personal process by eminent persons such as Poincaré (Boden, 2004) or Einstein (Einstein, 1982). Despite its age, this is still an influential view, featuring in some form in far more recent works (Simonton, 1999, Hayes, 1989).

Within design, more recent work has focused on the creative leap and its characterisation – incubation and illumination within Wallas' model - perhaps one of the more unusual elements of the creative process. Although some work, particularly earlier in the field, will describe the creative leap as a vague occurrence somewhat beyond detailed study (see Boden (2004) for an excellent discussion), much research in more recent years has focused on its appearance, and those factors which may encourage it. Highlighting the sudden realisation of a solution that surprises the designer, Akin and Akin (1996) argue that the creative insight stems from the removal of an unnecessary constraint on design that allows a new solution to appear. Looking at the sudden realisation of common ground between a problem and solution, Dorst and Cross (2001) consider the "creative leap" to be more of a "creative bridge". During the design process, they argue that a subject or theme may appear that can be related both to the problem and desired solution states, which can be steadily built upon to produce a creative solution. In a detailed discussion, Boden (2004) argues that even some of those who advocate a creative leap to a solution from nowhere are often in truth pulling from ideas that have been steadily built with time.

2.4.2 The Appearance of Creativity

A key factor in the definition of a creative solution is both originality and appropriateness in solution. For these to occur, particularly in cases where their appearance is marked, it is necessary for the designer to produce a solution that has not been seen before and is also highly suitable, often with capabilities beyond past alternatives. Such an appearance is somewhat dramatic, and may lead to the "why wasn't that thought of before?" interpretation often associated with a creative leap. However, as argued by Boden (2004), a creative leap will often come from study and detailed understanding built up over time. While it may be the case that a sudden elucidation of a possible solution, concept or opportunity will lead to a creative product, this can be the directly traceable result of much work. Equally, a highly creative product may stem not from a significant and sudden leap but from a detailed development of the design with time, to the point that the solution matches the definition of creativity. In any case, the point at which a designer realises the form that their solution may take (the creative leap) is not the primary focus, rather looking at the behaviour throughout the process that led to this realisation, and beyond to the final solution.

In every case, the creative product is brought about by behaviour of a designer. Their detailed study may include all of the necessary elements to allow a sudden creative leap to occur, or it may simply build step-by-step on a design until the design is a highly creative product. The important factor within context of this work is that the actions of the designer in both cases lead to a product that is highly original, highly appropriate to the design problem, and surprising in its output. It is therefore the study of these actions, whether a leap occurs or not, that hold focus within this work.

2.4.3 Routine Design and Creative Design

Given that the creative process is a result of the behaviour of the designer, it is now the task to determine the features of creative behaviour that allow it to produce a creative product (or conversely, those that prevent it).

Within the literature, some approaches classify forms of design by their inherent creativity, separating between non-creative *routine* design (Brinkop et al., 1995); and two categories of non-routine design: *creative* design (Chakrabarti, 2006) and (in some cases) *innovative* or *variant* design (Dym, 1994, Gero, 2000). There is however some confusion and complication between these terms, stemming from a lack of distinction between exploration for the sake of the design outcome, and exploration in order to find a way to continue the design process itself.

As according to Brown (1996), routine design can be described as a reflection of the experience of the designer completing the task. In cases of higher experience a designer will have more knowledge of the design situation, will be able to utilise previous methods, and will therefore be able to follow a well-understood approach to reach a solution. In cases where the experience of the designer does not form a well-understood approach, it is necessary for them to find an approach, or develop one. This is therefore an example of non-routine design. Such a definition is therefore similar to the interpretations of Gero (2000) and Dym (1994), stating that *routine* design occurs when a designer knows all required information to produce the final product, but is not identical – the definitions of Gero and of Dym do not account for the difference between exploration in the process to follow and exploration of the design itself.

Within creative design, by the definitions of Gero (2000) and Dym (1994), the creative design process includes the introduction of new variables or knowledge into the design (termed *creative* by both); or includes either the removal of context which constrains the values that variables can take (thus allowing variables to take unexpected behaviours), or a lack of understanding of how present knowledge should be applied for the design to progress (termed *innovative* and *variant* design respectively). Therefore non-creative design occurs when all variables and knowledge are known, none are introduced, and none are used in new manner.

The issue here lies in distinction between exploration for the sake of developing the design, and exploration for the sake of finding a solution strategy. Gero and Dym do not make a distinction – any form of explorative behaviour is classed as creative. Through this definition however, study loses some of its nuance. Exploration for the sake of the design will produce solutions that are creative. Exploration for the sake of solution strategy may, but only if the solution strategy encourages the exploration of solutions for the design.

Table 5: The distinction between routine and creative

Creative Behaviour	Non-creative Behaviour
Routine – A well-understood approach to the problem exists, and involves exploring new variables or knowledge for use in the design.	**Routine** – A well-understood approach to the problem exists, and does not involve exploring new variables or knowledge for use in the design.
Non-routine – A well-understood approach to the problem does not exist. The design must find or identify one, and the followed approach explores new variables and knowledge for the design.	**Non-routine** – A well-understood approach to the problem does not exist. The design must find or identify one, and the followed approach does not explore new variables or knowledge.

In order to distinguish between creative and non-creative, routine and non-routine, this work makes the distinction alluded to within Brown (1996) and omitted by Gero (2000), (Dym, 1994). Creative and non-creative design concern the development of the design outcome itself; routine and non-routine design concern the solution strategy that is employed. These two categories are therefore mutually exclusive (see example in Table 5).

The focus of this work lies on the process by which a designer produces a creative result, and as such is concerned with creative/non-creative behaviour as defined here, rather than routine/non-routine behaviour. The formal definitions of creative and non-creative behaviour are given in Table 6.

Table 6: Definition of creative behaviour

	Definition
Creative behaviour	Behaviour during which the designer explores new variables and/or knowledge to be used to develop the design, or explores new ways of using current variables and/or knowledge.
Non-creative behaviour	Behaviour during which the designer does not explore new variables and/or knowledge, or the possible manner of the application of current variables and/or knowledge.

2.4.4 Divergence and Convergence

The definitions of creative behaviour link closely with literature in regards to divergent and convergent behaviour, as originally proposed by Guilford (1956); the former expanding options through exploring a range of possible solutions and information; the latter discriminating between and among these to develop a single, highly suitable result. This model has had wide influence within creativity and design literature, usually placing divergence and convergence as iterative stages leading to a single solution (Pugh, 1990, Cross, 2000), see Figure 7.

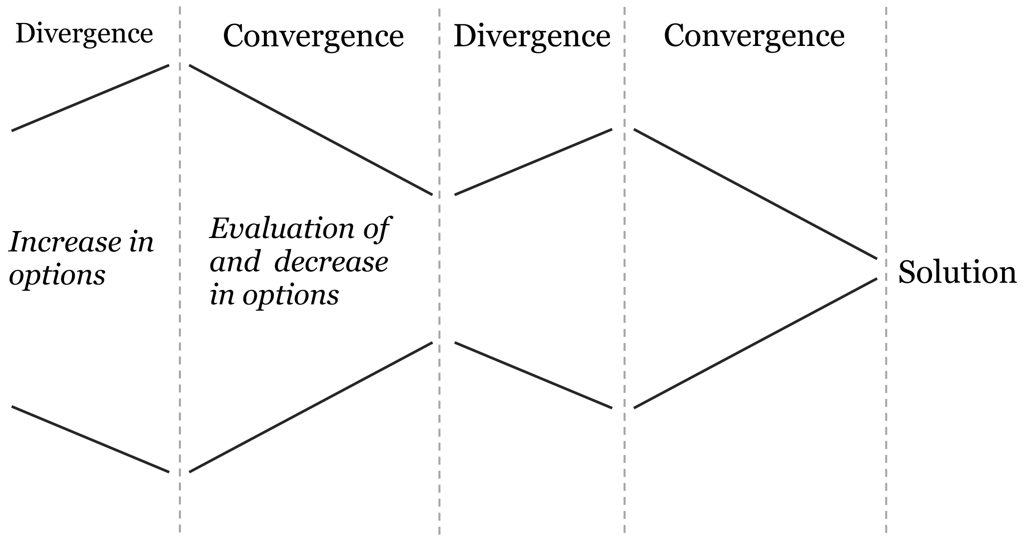


Figure 7: Divergence-convergence in design, after Cross (2000)

Within a divergent process, a designer will explore possible options, alternatives, and sources of information for design. In the scope of much design, where large amounts of information will not be present at the outset, divergence of some form will be a common occurrence (Liu et al., 2003). As such, using the terminology of Gero (2000) and Dym (1994), divergence represents the process by which a designer will explore new variables or knowledge, or the effect of using variables and knowledge in new and unexpected ways.

Within a convergent process, a designer will evaluate and select information and solutions in order to narrow their alternatives, culminating in a single solution for further development. This process can also involve creativity (Cropley, 2006), in that the designer can explore alternative variables and knowledge for the design during their evaluation process. When creative, this lies parallel to the definition of creativity as through exploration of how variables and knowledge may be used in design, termed *innovative* design by Gero (2000) and *variant* design by Dym (1994).

Exploration in design, divergence, some forms of convergence, and creative behaviour can be seen as highly inter-related. To perform divergent behaviour requires exploration of variables and resources for design, and so demonstrates creative behaviour. To creatively converge requires exploration of how variables may be used within a design, and so is also indicative of creative behaviour.

The appearance of exploration

Exploration in design may appear in a number of ways. Beyond and within typical methods such as brainstorming (Niku, 2009, Osborn, 1953), exploration occurs at a lower level, closer to the cognitive processes of the individual designer.

For example, Gero (1996) describes creative behaviour through its bringing out of emergent properties. Within an identical design situation, a creative product may arise through recognition of new possibilities or opportunities that appear as the process continues. The creative behaviour does not take the form of direct exploration of many variables, but the branching off from the “expected” solution along the newly recognised opportunity. This is still an example of exploration, the designer was exploring potential opportunities, which manifests through multiple solution concepts – that which would occur through following the non-creative process and that which results from following the new opportunity.

Others consider creativity as a result of association between separate concepts (Mednick, 1962, Gero, 1996), in a similar manner to creativity as through analogy (Goel, 1997, Chan et al., 2011). Here, exploration is only indirectly related to the design outcome, rather concerned with exploration of analogical targets and their application to the design. As the eventual impact of this behaviour is to the design, and not to the solution strategy employed, this is also considered creative behaviour.

2.4.5 Key Considerations of the Creative Process

The key feature of the creative process within this work is that it is a distinct entity from either the creative person or the creative product. This perspective encourages the study of all processes and of behaviour within directly, rather than study of the process indirectly through the results that it produces; and acknowledges that creative behaviour may not always lead to a creative product dependent on the many external influences under which a designer works. In other words, and according to the definitions within Table 6, creative behaviour may not always lead to the production of a creative product, and so may not always be classed as belonging to a creative process. That some examples of creative behaviour lead to a creative result and some do not potentially adds a further layer of depth to understanding.

This definition of creative behaviour as any example of divergence or creative convergence through exploration also has impact when considering the engineering design process itself. Typically, and as will be explored in Section 4.5, creativity is considered to occur in earlier design stages, when fewer decisions have been made and the design process is more open. However, it is equally valid to say that designers can be creative in later stages of the design process, within higher levels of complexity and constraint. Although the results of creative behaviour at these stages may differ (Eckert et al., 2012), some form of exploration will still occur, and hence so will creative behaviour.

It is through creative behaviour that this work studies engineering design, and the manner in which creative products come to be. This focus allows broad consideration and comparison of different designers, different products and the different processes that they follow; while concentrating on key, traceable elements of the design process.

2.5 The Creative Context

As a re-terming of the pillar of the creative *press*, the creative context states the importance of considering the designer and the world in which they reside as a whole, rather than separate entities (Rhodes, 1961).

It therefore concerns an incredibly broad range of subjects, and has been the subject of much research. For example, the impact of team-working on creativity (see Pirola-Merlo and Mann (2004)), the spaces in which designers are working (Amabile et al., 1996), the domain (Feist, 1999), social factors in creativity (Csikszentmihalyi, 1999), and creativity within culture (Lubart, 1999).

2.5.1 Applicability of the Study of Creativity

A prime issue of consideration of the creative context is that it greatly widens the focus of research. As studied in Chapter 10, the role of context on what is interpreted as creative or non-creative is profound. Dependent on domain, designer, design situation, society, or more, different people will consider different things to be creative. Many of these factors can be studied through the creative context, and act to temper understanding. This puts the other pillars into context; while research and evidence may be accurate and reliable in one situation, care must be taken when generalising to another. As such, it is an important subject for research.

Within this work, the focus of research lies firmly within engineering design; the target of which is some form of direct product or output, through a process often completed by a designer. Therefore the context within this research is well understood. Detailed consideration of the context beyond this situation (and applicability to others) is not vital for progress or understanding – although it would be necessary if the result of the research were to be broadly applied in, for example, different design domains or substantially different cultures.

Beyond characterisation in context, the pillar of the creative context can therefore be considered an additional variable beyond the primary scope of research. Although its study may provide valuable additional insight in future work, to maintain high focus within this research it is sufficient to study in detail the creative person and creative process, and how they develop a creative product.

2.6 Summary: The study of creativity

Creativity as a concept demonstrates both some form of benefit or improvement within an output, but also the role of an active creator, or observer who judges it to be so. It is possible to judge any artefact as creative (and so it is possible to study what makes it so), but it is also important to study the role of the creator and their influences, what they do to produce the creative artefact, what characteristics allow them to produce it while others might not, and even how they are influenced throughout creation.

This gives a wide expanse of scope, which was given structure through the four pillars of creativity (Rhodes, 1961). None of these are sufficient for understanding alone, but together form the basis for understanding.

Product *– The creative product concerns the design output, be it physical or not, and the methods by which it is judged to be creative.*

Person – *The creative person concerns the designer and the characteristics, skills, and abilities that allow them to produce a creative product.*

Process *– The creative process concerns the method by which a creative product is created, particularly the behaviour of the designer that encourages the generation of a creative result.*

Context *– The creative context concerns the environment and external influence under which the design is working, ranging from physical surroundings to communication, relationships, economics, social, economic, and cultural factors.*

It is through these four pillars creativity can be studied, and through the structure that they create that the research presented here progresses.

2.6.1 Perspectives of Creativity

As has been alluded to throughout the chapter, there are different opinions within literature on what may be interpreted as creative.

Some focus on more objective criteria, such as measurement of characteristics of creative outputs and determination of a person's inherent creative level or style (see Sarkar and Chakrabarti (2011), Shah et al. (2003), Chakrabarti and Khadilkar (2003), Kirton (1976)). In this sense creativity is manifest in each of the four pillars, for example through characteristics in a product, tell-tale activities in a process, or specific traits of a person. To study creativity is then to study an amalgamation of inter-relating properties, which will by definition lead to an increase in, for example, output quality or process efficiency.

Others focus on creativity as an occurrence within a process that is very difficult to study directly. Beginning with arguments for incubation and illumination as vital components of the creative process (Wallas, 1926), such research has focused on how a creative solution comes to exist, and the moment of sudden realisation of the potential form of a solution that can occur (Akin and Akin, 1996, Dorst and Cross, 2001). Despite considering creativity as a more nebulous concept, this view still recognises that a creative solution will still be built upon much prior research and work (Shneiderman, 2000, Boden, 2004), but places focus firmly on the process of creativity rather than the result.

A third perspective considers the importance of context of creativity and of judgement in its interpretation. Regarded as a human construct and therefore only interpretable through a human perspective, this view claims at its extreme that creativity only exists in the mind of the person who is assessing it; while shared understanding does exist, it is always context dependent to some extent (Shalley and Gilson, 2004, Amabile, 1996). Study of creativity is then the study of why a product is viewed as such, allowing focus on elements of a creative process or product that encourage a creative interpretation (see Amabile, 1996, Csikszentmihalyi, 1999), within the appropriate context. Although it cannot be considered a topic for objective study, consistency between persons and understanding of what is needed in context then allow understanding of creativity and the benefits it may bring.

2.6.2 Creativity within this Work

Through interpretation and the implications of these perspectives on creativity, this work can frame its perspective of the four pillars of Rhodes (1961).

In terms of the pillar of the creative product, it is very difficult to classify what is creative and what is not; opinion can vary between judges, or even from the same person in a different context. However, although not conclusive, there are some useful metrics that have been demonstrated as measuring important and consistently appearing characteristics of better results. By keeping these metrics under consideration, it is likely that at very least an improved solution will be reached.

The pillar of the creative process is highly variable. Considered as separate to the product, it will contain steps or activities that encourage (but do not guarantee) a creative result. Considering the variety of processes that exist and contexts in which they occur, there is likely no particular well-defined structure to the creative process; although descriptions of creative behaviour and the need to produce originality and surprise in output imply the need for divergence and creative convergence.

Similarly, although distinct traits of creativity in the pillar of the creative person exist, there is a broad variety in styles and abilities, completed activities, product, design situation and context.

This work then proposes the structure for the four pillars shown in Figure 8. While high quantities of iteration and inter-dependency between each pillar exist, in a general sense the creative design process consists of an individual process completed by a person, with a goal of a product that displays characteristics which will be interpreted as creative. This designer is working based upon their own experience and within a specific design situation that may include a multitude of influences; from team work, to department structure, to design specification, and to design problems or changes. However, consistency exists in that every case concerns the development of a product of some form, designed by a designer within an understandable design situation, as they follow an observable process.

Figure 8: Proposed structure of the four pillars

It is this understanding, then, that frames the study of creativity within this research. In order to effectively study the appearance of creativity it is necessary to study the process and appearance of creative behaviour directly. As this element is a consistent presence within engineering design this is a significant advantage, allowing both comparisons across products, designers and design situations, as well as deeper understanding than can be found through study of the creative product alone.

Further, as there are likely significant variations between designers even when working on identical projects or in identical design situations, it is necessary to consider them both explicitly and individually to fully understand the influences and variations. Without consideration of the person, understanding of the process is incomplete. This is not to say that study of teams is not useful, only that focus within this work will lie on individuals first.

The context in which the designer works is also important, surrounding understanding of each of the other pillars. Engineering design and industry provide this context within this work, as will be presented in Chapter 10, thus describing the creative press in which a designer's creative behaviour occurs.

Chapter 3:
The Engineering Design Process

The engineering design process has been studied for a number of decades, resulting in formalised understanding of its structure and purpose. As a result there are now many models of the process as a whole (see Pahl and Beitz, 1984, Pugh, 1990, Ullman, 1997, Cross, 2000), describing all of the activities that a designer must complete throughout each stage of the process, the considerations that they should make, and how they can ensure they develop a successful solution.

It is within this context that this thesis occurs, and the field of engineering that the research is deployed. It is therefore important to develop a good understanding of the form of the engineering design process and its deployment, the role that individual designers play within it, and the role of creativity and creative behaviour. The field of engineering then provides contextual constraints on study – the role of design in engineering is different to that in fields such as art, as are the characteristics and requirements of designers working within each (Fricke, 1996).

It is this context that this chapter will address. Using the many formal models of the engineering design process as a base it will describe the structure of the design process and how it can be classified, the difference between activity and behaviour, and the role of the designer within.

In addition, and following the primary focus of this thesis, this chapter describes the particular characteristics of later stage design that define it as different to early stage design, and to the design process in general. This chapter then also provides context to the knowledge gap as described in Chapter 4.

3.1 The Engineering Design Process

The intent of models of the engineering design process is to provide structure, allowing understanding of the activities that theoretically must occur for a design to be produced. Many different versions have been proposed over time and have gained good acceptance, although at a general level many follow a similar pattern (Howard et al., 2008a).

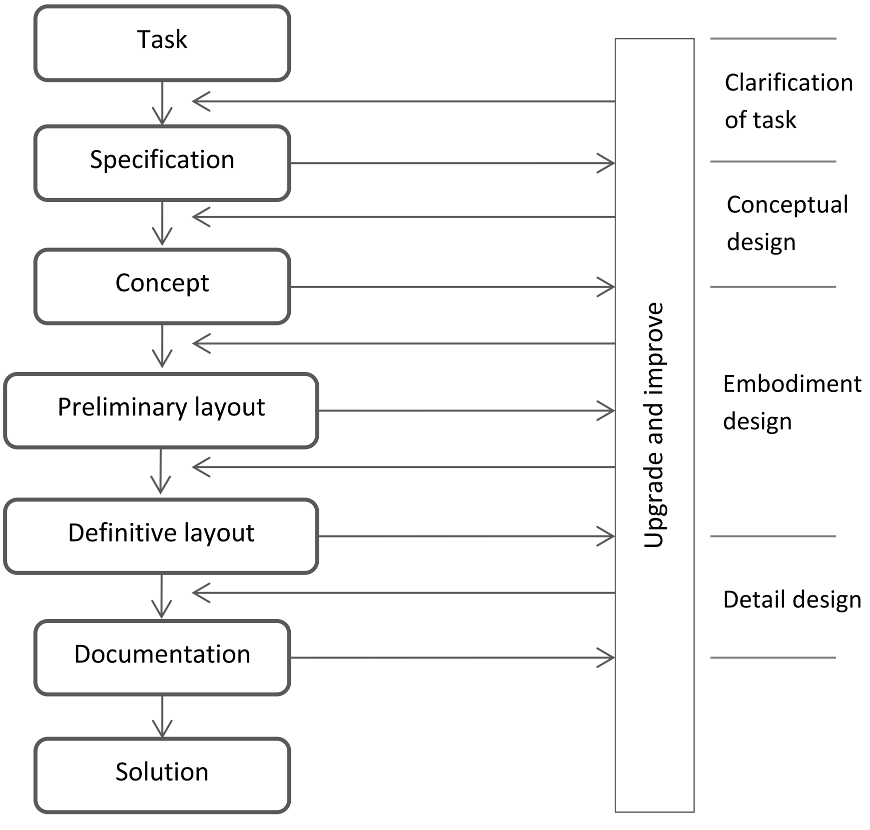


Figure 9: The engineering design process (Pahl and Beitz, 1984)

Due to their place in design research and engineering industry, two different types of models of the engineering design process have been proposed; one with a focus on *description* of a designer's process, and the other that attempts to *prescribe* what a designer should do.

The former of these presents description of the tasks completed by a designer throughout their design process (Cross, 2000), primarily with a theory-building role (Ullman et al., 1988b). From understanding of what designers actually do, it is possible to form implications relating to improvement and support of the design process, design education and project management. Conversely, a prescriptive process aims to present a systematic representation of the design process in a generalisable form (Cross, 2000). The purpose for these systematic models (such as those of Pahl and Beitz (1984)) is practical – based on assumptions such as increasing complexity as the design field evolves and increased risk within large-scale projects, well-understood processes of design both provide a structure and understanding to management, and a means to encourage good design behaviour and efficiency.

Although there is significant similarity in the process that many models present (Cross, 2000, Howard et al., 2008a), descriptive and prescriptive models concern fundamentally different subjects. A descriptive model looks solely at a designer and what they do, their behaviour, in order to gain understanding of a general design process as a whole. A prescriptive model suggests activities that a designer should complete, in order for a product to come about in an efficient and manageable manner. These behavioural tasks and process activities are not directly synonymous.

Within any process activity, a designer will complete one or many behavioural tasks in order to achieve the activity goal. For example, to assess the loading on a beam, a designer will perform calculation, followed by evaluation against some requirement. Within this activity, different designers will complete different tasks and still achieve the same result (e.g. hand-calculation vs. simulation vs. rule of thumb vs. experience-based judgement), with their actions based on personal experience, abilities and decisions. Furthermore, any task completed by a designer can be for the purpose of a multitude of activities (e.g. calculation as evaluation, as exploration, or as an input into further design). This relationship between task and activity is further discussed in Section 3.2.

Due to the purpose of descriptive and prescriptive models, their form is entirely logical. In order to gain understanding of the design process it is necessary to study a designer's tasks – descriptive models provide a detailed grounding on which research can build. In order to manage and influence the design process in a useful manner, it is necessary to suggest processes and better ways of working – prescriptive models provide this structure and consistency. This difference underlines the implication within design research; when the purpose is to study, understand and characterise designers, it is necessary to descriptively study behaviours within context of the activities that they are completing. This understanding can then be used in a more prescriptive sense, supporting and influencing activities throughout the design process with consideration of the types of task that a designer will complete.

It is also worth noting at this point the role of the intended output of the engineering process in relation to the process followed. Looking towards literature focused on types of innovation within the market as is prominent in management literature, products can be described as incremental or radical innovations in nature (Abernathy and Utterback, 1978). An incremental innovation in this context refers to one in which a new product is developed based on a previous version, and so is incremental in its newness to the market, while a radical innovation refers to one which is new in large part to the market, perhaps due to a major technological advancement. Such differences in output require different forms of management and different initial conditions for the project in which they are developed to succeed (Dewar and Dutton, 1986, Koberg et al., 2003), but remain within the bounds of engineering design and, as such, within the bounds of the engineering design process as observed and modelled. It is important to remember, however, that the content of a design process and the expectation for its output will vary greatly depending on the context in which the design occurs and, as such, the process actually followed by designers as part of their design behaviour has potential to vary greatly.

3.2 Activities and Tasks

The difference highlighted between descriptive and prescriptive models is in perspective; that one describes the process through the tasks of the designer, and the other describes the process through activities that it should include. To fully understand the practical implication of this difference, it is necessary for it to be placed within some structure.

Activity Theory (AT) (Kaptelinin et al., 1995, Collins et al., 2002) is a conceptual framework primarily developed within Soviet Russia, although its roots reach throughout the last century. It is highly objective in its nature, stating that the human mind can only be understood through the interaction between human beings and their environment. These interactions are defined as goal-oriented, socially determined activities, with a structure that is highly applicable to the role of designers within the engineering design process.

AT has gained traction in some design-related fields, particularly computer engineering and Human-Computer Interaction (HCI) (see Redmiles, 2002, Kaptelinin et al., 1995, Karlsson and Wistrand, 2006), although direct application within engineering design has not been found. Within research, AT is used to provide a general framework around which more specific theories can be developed (Kaptelinin et al., 1995), using its objective nature to analyse subjective criteria within context of their socially determined status.

AT is based on the premise that the mind is studied through its interaction with the environment (termed *activities*), towards a specific goal (termed *objects*). Implied within is then the concept of an agent performing the action (a *designer* in this case), and a subject of activity (termed *object*). Around this concept, AT provides several principles, including activities as internal or external, the role of tools, and the structure of activities.

It is the last of these that is useful here. AT states that there are three levels within a hierarchical structure - at the top are *activities*, interactions between designer and artefact motivated by a specific goal. Beneath *activities* are *actions* – these implement the activity, with a goal of completing the activity. Actions can be described at varying levels of granularity, any action may be comprised of sub-actions and sub-goals, or similarly may be a sub-goal to the higher levels of actions. At the lowest level is the point at which actions become mental operations – each mental process does not explicitly hold its own goal, but through their accumulation actions are completed.

This structure applies closely to the description of the design process as a series of activities that must be completed within a prescriptive model and behaviours that a designer completes within a descriptive model, as well as highlighting the role of cognitive or lower-level designer actions. A design process *activity* of a prescriptive model can be seen as equivalent to an activity within AT. It is the highest level interaction between the designer and the artefact. In a design sense, it is the activity that must be completed, with a goal of progressing the design process. The design process *tasks* within a descriptive model can be seen as equivalent to *actions* within AT. They are the actions of the designer that complete an activity, with a goal of completing that activity. In a design sense, they are the series of steps that a designer will perform, in order to complete a design activity. The designer then completes their tasks through a series of cognitive operations, equivalent to the relationship between operations and actions in AT. Within this work, the terms *activities* and *tasks* take definitions from AT, with examples of each shown in Table 7; terminology is here changed from that of AT, to terms more recognisable within the engineering design research field.

Activity Concerned with the design process rather than the design itself, this term describes discrete elements within design process stages with a single specific goal, such as determination of design requirements or selection of design layout.

Task Concerned with the production of the design itself by the designer within the design process, this term describes the discrete elements within a specific activity, each with its own specific goal, such as individual calculation, individual application of layouts or gathering information regarding a specific subject.

Table 7: Activities and tasks within the design process

Activities (Hales, 1986)	Activities (Pahl and Beitz, 1984)	Potential tasks
Select layouts	Select suitable preliminary layouts.	Concept re-design Concept evaluation Functional analysis
Auxiliary layouts	Develop detailed layouts and form designs for the auxiliary function carriers and complete overall layouts.	Patent searching Part configuration Functional analysis
Optimise form designs	Optimise and complete form designs.	Stress/strain analysis Dimensioning Computer simulation

3.2.1 A Formal Definition of Behaviour

This formal distinction allows more focused research. The design activity describes the interaction between the designer and artefact from a process perspective, what the designer must do at a particular point in the process to progress. The design task describes the actions of the designer (termed design *behaviour*) that completes these actions. As set forth within AT, these are separate elements that can be studied individually, but must be understood in context of the other components. It is therefore understood that to complete a certain activity a designer must complete a series of tasks, but that these tasks can vary between designers or design situations. Furthermore, through the study of these tasks it is possible to gain better understanding of the design activities.

This thinking informs the formal definition of behaviour used throughout this work. In the initial nomenclature, behaviour is defined as:

Behaviour The mental and physical tasks completed by a designer over time, through which individual activities are completed.

This definition aims squarely at tasks (actions within AT) for the study of behaviour of designers. Activities as understood within this work are individual stages of the design process, often formalised through models. Tasks are the actual occurrences completed by a designer in order to meet the goals of the more formalised activities. It is therefore tasks that reflect the designer, while activities reflect the process. The implication of this is that even within identical activities designers may complete different tasks, and hence display different behaviours.

Behaviour cannot be determined from a single task. It is through groups of tasks that patterns can be observed, and behaviour can be quantified. The definition of behaviour must therefore include a time dimension of some length, to be quantified depending on the time period of interest.

Tasks can be examined at multiple layers of granularity, and hence so can behaviour. Actions within AT are a hierarchical structure continuing down to the level of automatic cognitive responses, theoretically to the level of biological processes. Study of behaviour can then occur at any level of granularity to which analysis of tasks occurs. At very low levels, this may be classed as cognitive behaviour – the individual thinking processes that designers complete. At higher levels these are more tangible occurrences related to process activities.

Creative behaviour as generally defined in Section 2.4 then refers to a sequence of tasks completed in such a manner as to make a creative result a possibility. The assumption here is therefore that the manner in which such tasks are completed, either individually or as a group, are encouraging of finding solutions that are original, appropriate and surprising.

3.3 The Form of the Design Process

The engineering design process is described by many different models, each with slight variations or emphases on different aspects, dependent on their intended use. For example, models such as that of Pahl and Beitz (1984) and the VDI guidelines (VDI-Richtlinie, 1993) use quite strict design stages, with highly prescriptive check-list type series of activities within; while models such as the Total Design Model (Pugh, 1990) advocate a freer process, involving development and learning through iteration. In general, however, process models can be described as containing four specific stages; clarification of task, conceptual design, embodiment design and detail design (Howard et al., 2008a). In addition, several models also include a stage before in which the initial need for a product is identified, and a stage afterward in which implementation and production of the produce occurs. Beyond engineering too, the design process can be described as conforming in a general sense to these stages, such as in the product development process of Ulrich and Eppinger (2012) or Roozenburg and Eekels (1995).

These prescriptive stages provide a necessary general structure, by acknowledging that design process activities and designer behaviour will change throughout the process it is possible to focus research, concentrating on changing needs at different points and providing appropriate support.

Some care must be taken, however, in how these design stages are defined.

3.3.1 Chronology and Hierarchy in the Design Process

Considering the structure of prescriptive models of design it is tempting to define design stages in a linear, chronological manner, in which those activities that occur at an early point in time are classed as early stage, and those that occur at a later point in time are classed as late stage. However, there are two issues with this description, namely the roles played by iteration within the design process, and by system level at which the designer is working.

3.3.2 Non-linearity in Design Processes

In reality, no single sequence of steps can describe a design process. Within any, the uncertainty of changing specifications, design problems, complexity, and even human nature will cause some fluctuation and re-work. For this reason, it is common for design process models of any type to stress the importance of iteration (see Dixon (1966), French (1971), Pugh (1990), Antonsson and Cagan (2001), Pahl and Beitz (1984)). This is an integral part of the design process, using new knowledge to improve the re-work and improve the design, or repeating steps to mitigate or solve problems, and has been demonstrated to improve the quality of process output (Smith and Tjandra, 1998, Berends et al., 2011).

Although recognised in all, the extent to which iteration plays a role in the design process differs within models. Ranging from the cyclical, descriptive model of Knott (2001) to the prescriptive and algorithmic models of Pahl and Beitz (1984) and the VDI 2221 Guidelines (VDI-Richtlinie, 1993), perspective on iteration ranges from the central driving force behind design to a necessary but separate occurrence.

The implication of this is that design stages must be decoupled from a pure time dimension. At any point in the process a designer may move “backwards” according to the prescriptive steps, repeating both tasks and activities that they completed at an earlier stage. Conversely, a designer may also at any point briefly dive into significant depth in a single area only to quickly return to a more abstract level. This occasional depth-first exploration is an observed solution strategy in engineering design (Ball and Ormerod, 1995), and is discussed in Section 4.3. To define stages purely by time would then potentially provide little difference between each; early stages by time may contain episodes of depth that mirror typically late-stage activities, while later stages by time may contain iteration that mirrors typically early-stage activities. To use time as a definition for design stages would then prove ineffective for the purposes of comparison.

3.3.3 System Level Variation in Design Processes

As noted within literature (Howard et al., 2009), an alternative method of describing design stages is by level of system decomposition (referred to here as a hierarchical method).

Regardless of purpose or form, all products can be broken down into their constituent functions, creating a hierarchical structure leading from the high level main function, to the sub functions by which it comes about (Suh, 1990, Hirtz et al., 2002). Each of these functions can then be mapped onto a specific system, sub-system or product, which together create the product itself (Ulrich, 1995, Ulrich and Eppinger, 2012), as seen in Figure 10. This classification can continue to further levels of granularity, sub-dividing to the individual components that form each sub-system and through which functions occur.

Decomposition such as this may then create a distinction in level of detail dependent on the place of the function or product within the hierarchy. Those that lie at a low level are of a higher level of tangible detail than those at the top, while those at the top may then be considered more conceptual (Howard et al., 2009). Hence it may be thought that *detail design* does not refer to the tasks that lie towards the end of the process, but to a lower level in the system hierarchy.

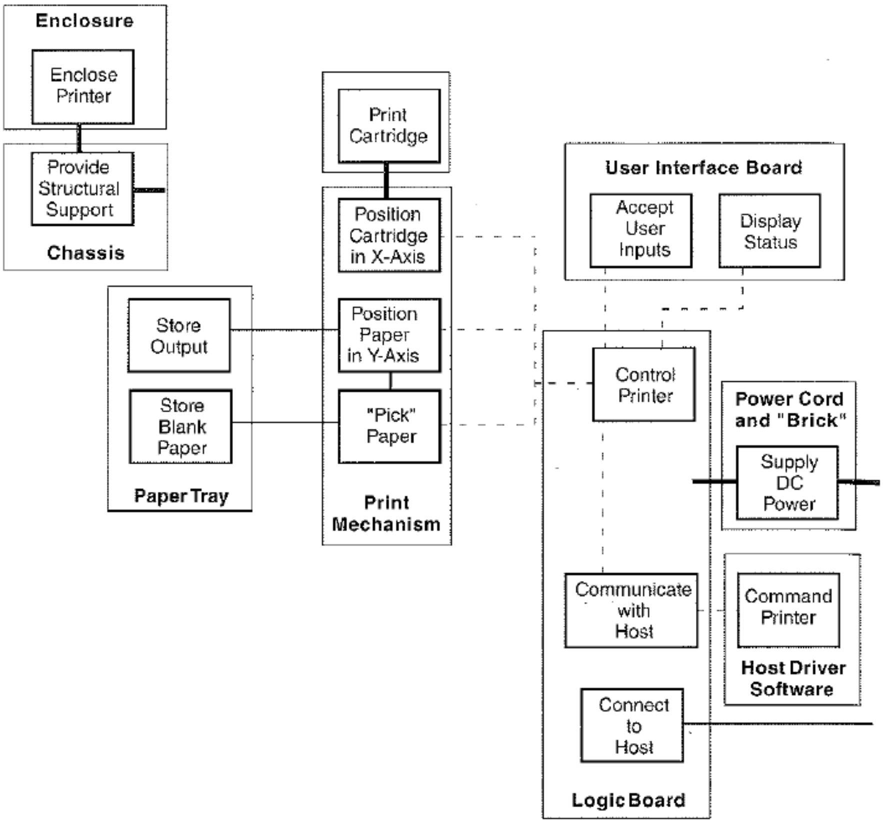


Figure 10: Functional and component hierarchy or a printer, from Ulrich and Eppinger (2012)

Considering the activities of prescriptive models, a purely hierarchical view also gives little differentiation between design stages. Regardless of whether the designer is considering system or component, it will be necessary for them to complete many different design process activities. It is equally necessary for a designer to assess the performance of an individual component within a printer, as it is to assess the performance of the printer as an entire system. In reality, it is entirely possible for each system or component at any level of system decomposition to go through an entire prescriptive design process, shown in Figure 11 (Howard et al., 2009). Accordingly, to define design stages by hierarchy would again be to state that any design activity or task could occur at any design stage, providing little structure for research.

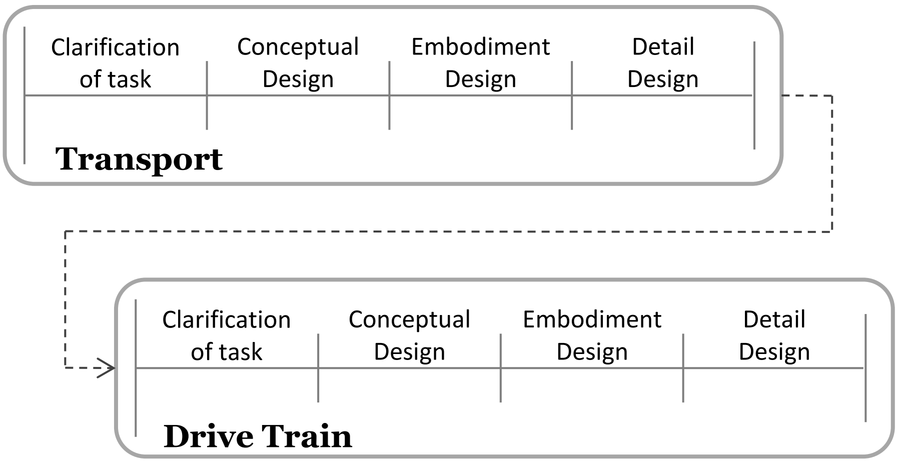


Figure 11: The design process at different systems levels, after Howard et al. (2009)

3.3.4 Design Stage by Focus of Activity

To accommodate both the linear and hierarchical views, this work then defines each design stage by purpose; the end goal of each stage through which the designer completes the whole process. This view is not unusual within the literature, with similar interpretations including that of Huang and Kusiak (1998), Howard *et al.* (2008a) and Ullman et al. (1988b); while influences can be seen from the work of Gero (1990), Pahl and Beitz (1984) and Deiter and Schmidt (2009). Evidence of a similar approach can also be seen in product development process models such as that of Ulrich and Eppinger (2012), which describes certain activities as spanning multiple “stages” of design, such as industrial design being an important part of conceptual, system-level and detail stages; and prototyping being a part of all stages of design from concept to testing.

By this method, definition of design stage is malleable, variant depending on the focus of what is being worked upon rather than on the actual task at hand; and thereby avoiding the pitfalls of categorising tasks that are different in nature as similar simply because they occur on similar level parts in the system hierarchy or at a similar point in time. For example, all cases of materials selection would be classed as detail design regardless of whether they occurred at an early or late stage; or on a large system or individual component (see definitions in Table 8). This creates significant differences between design stages; activities and tasks with a different purpose are placed in different stages, regardless of time of occurrence or system level.

Table 8: The stages of the engineering design process

Design Stage	Definition
Analysis	Determine the desired and required functions of the system, for it to complete its purpose.
Concept	Conceive the system functions in detail through preliminary description of system behaviour.
Embodiment	Design detailed system behaviour through preliminary description of system structure.
Detail	Design and finalise system structure, and all aspects that may influence it.

3.3.5 Analysis Stage

The purpose of this stage is similar to that commonly placed as the “task analysis” stage. Here, the designer must determine the purpose of the design, identify and understand the problem, and perform research that will allow them to continue. Additionally, they must determine in a basic sense what functions the product or sub-system will need to complete in order to fulfil the purpose. There is little direct, physical consideration of the product at this stage, instead concentrating on the background and context in which it will exist.

It is important at this stage that designers interpret the design problem appropriately, in order to produce a good result (Ullman et al., 1988b). Research into this stage of the design process has focused on subjects such as problem understanding and requirements (Nguyen and Shanks, 2009), and how designers will initially structure problems (Ho, 2001, Cross, 2004a); in order to encourage the designer to follow a good process, and to produce a result that solves that design problem well.

3.3.6 Concept Stage

The purpose of this stage is to determine what functions are needed to complete the product purpose and what technologies or systems could be utilised in order to complete each function. As a necessity to this, preliminary definition of the behaviour of the product will occur through designing the placement for various technologies within the overall system. This enables the designer to work out in general terms the method by which the final product will complete its function.

In terms of focus and freedom on the design output, this stage is typically considered more open than others. As the purpose of this stage is to produce the fundamental method by which a design problem will be solved, research has considered ideation and how an appropriate solution structure may be found (see Howard et al., 2008b, Shah et al., 2003), through the design process itself (Dorst and Cross, 2001) or creativity methods such as brainstorming (Osborn, 1953) amongst many others (see Niku, 2009).

3.3.7 Embodiment Stage

The purpose of this stage is to design, in detail, how the product will behave to complete its function. This includes detailed description of the layout of the components, how they will interact and how, together, they can contribute to both the functions of the sub-systems and the overall function of the product. This process will also include preliminary design of the structure of the product, basic sizing of components, appropriate analysis of any forces or stresses, and ensuring feasibility of assembly.

Research on this stage has focused on subjects such as configuration and optimisation of systems through computational means (Chakrabarti et al., 1992, Scaravetti et al., 2006), dealing with complexity and engineering change (Earl et al., 2005, Eckert et al., 2012) and the solution process of embodiment design activities (see Gupta et al., 2003).

3.3.8 Detail Stage

The purpose of this stage is to determine the structure of the product in detail, including detailed dimensioning of all components, all calculations and analysis that must be performed and fixings and interface design between components or sub-systems; as well as tasks such as designing components for ease of manufacture, minimal cost, or minimal material use.

Research into this area is hence far more specific to the subject matter than at other stages, steering away from the general process of detail design. For example, research into calculation has focused on methods of completion, such as of stress and material properties (see Budynas, 2008). Study of process here more closely ties to the specific purpose of the detail design task, with considerations such as design-for-production, assembly, or creep and relaxation (see Pahl and Beitz, 1984) providing guidance to priorities and process.

3.4 The Later Stages of Design

The different stages of the design process each have a different focus, and contain different types of activity. It is to be expected that certain similarities and differences between stages exist, that must be considered in research.

As will be discussed in detail in Section 4.5, the later stages of the design process have received little research concerning designer behaviour, especially within the context and structure of creativity research. The term *later stage* within this work is used to refer to the stages of the design process that this knowledge gap concerns, namely embodiment design and detail design. *Later stage* design is therefore a group of design stages that have received less attention, and does not imply that embodiment and detail design are grouped due to inherent process similarity, or that from a process perspective these stages can be considered entirely separately from earlier design stages.

With that said, there are some common differences between early and later stage design, which must be considered.

3.4.1 Process Differences between Design Stages

By definition, each stage of the design process has a different focus. Within analysis and concept stages, this is to develop and decide the system functional structure in full, which will by necessity include the fundamental system behaviour (Table 8). This will include relatively open activities such as problem space research and exploration of potential solution principles. The later stages are quite different in focus, primarily being concerned with the physical design, its layout, analysis and finalisation (see Table 9, showing the activities of the later stages of engineering design according to Hales (1986), Pahl and Beitz (1984).

Beyond fundamental focus, there are inherent differences between early and later stage design. Of the most basic of these is the role of constraints, which grow in number as the design process continues (Howard et al., 2011, McGinnis and Ullman, 1990, Ullman et al., 1988b). These can include the initial specifications and requirements of the design process, but also include the cumulative effect of working within decided solution principles, interfacing with other components and systems, and designing for tooling, manufacture and assembly once their type is chosen. As a result, designers working within the later stages of design must consider a higher number of constraints throughout their design process, reducing their freedom. This can have the effect of limiting the design space and increasing design process difficulty (Matthews et al., 2002).

An offshoot of the increase in constraint is that of higher design process complexity. Measured through the quantity of information and coupling between elements (Summers and Shah, 2010), a high amount of constraint and high quantity of finalised design decisions can increase difficulty of working within these later stages. For example, through required consideration of change propagation through systems (Eckert et al., 2004) or increased cognitive load (Van Merriënboer and Sweller, 2005).

Table 9: Activities within later stage design

	Hales (1986)	Pahl and Beitz (1984)
Embodiment Design	Review Concept	Identify embodiment determining requirements
	Spatial Constraints	Produce scale drawings of spatial constraints
	Identify Function Carriers	Identify embodiment determining main function carriers
	Preliminary Layouts	Develop preliminary layouts and form designs for main function carriers
	Select Layouts	Select suitable preliminary layouts
	Main Layouts	Develop preliminary layouts and form designs for remaining main function carriers
	Search for Solutions	Search for solutions to auxiliary functions
	Detailed Layouts	Develop detailed layouts and form designs to ensure compatibility between main and auxiliary function carriers
	Auxiliary Layouts	Develop detailed layouts and form designs for the auxiliary function carriers and complete overall layouts
	Check Layouts	Check and refine the overall layouts
	Evaluate Layouts	Evaluate against technical and economic criteria
	Optimise Form Designs	Optimise and complete form designs
	Review Design	Check for errors and disturbing factors
	Prepare Documents	Prepare preliminary parts list and production documents
Detail Design	Finish Drawings	Finalise details
	Integrate Drawings	Integrate overall layout drawings, assembly documents and parts lists
	Prep. Final Documentation	Complete production documents with manufacturing, assembly, transport and operating instructions
	Check Documentation	Check all documents for standards, completeness and correctness
	Remainder	

These differences distinguish later stage design from early stage design both in terms of focus and properties. For the purposes of study, this means that later stage design must be considered to some extent separately. To consider the design process as a whole would be too general, identifying few of the specificities of each stage; and to attempt to apply early stage research to the later stages would be problematic; it cannot be assumed that what is correct in one area is also valid in another.

Differences apparent in later-stage design relating to its process and influences are summarised in Table 10. In addition, this research considers differences in designer behaviour within later-stages, as is presented in Section 4.5.

Table 10: Process-based and situational differences apparent in later-stage design

Difference	Reference
Focused on the development of behaviour and structure	(Gero, 1990, Gero and Kannengiesser, 2004)
Higher constraint	(Howard et al., 2011, McGinnis and Ullman, 1990)
Activity focus on layout, analysis and finalisation	(Pahl and Beitz, 1984, Pugh, 1990, Ullman, 1997)
Higher design process complexity	(Eckert et al., 2012)

3.5 Summary: The Engineering Design Process

Models of the engineering design process provide understanding and structure of the processes that typically occur when designing products, both from the perspective of designer behaviour (descriptive models) and of idealised process (prescriptive models). From the context and understanding that these provide, it is now possible to begin to inform the primary research direction.

Due to the difference between activity and task, it is important that both are understood in detail. This is particularly true of tasks completed by designers and their consequent behaviour – which is variable between designers even when completing the same activities. Thus designer behaviour presents a subject of great complexity, but also a subject in which better and worse behaviours likely exist (as exhibited by the consistently higher performance of some designers over others (Ericsson and Lehmann, 1996)), hence providing the potential for great benefit. Through the study of patterns in behaviour that consistently provide good results, it may prove feasible to develop designer support and education that improves the general behaviour of designers, is applicable in multiple activities, and hence improves the outcome of the design process.

3.5.1 The Behavioural Design Process

At several points within the last two chapters a line has been drawn between a process perspective of the design process, and a behavioural perspective of the design process. This is common in literature, being a main difference between prescriptive and descriptive models of the engineering design process (see Cross, 2000, Pahl and Beitz, 1984, Pugh, 1990, Ullman et al., 1988b); a fundamental structure within Activity Theory (Kaptelinin et al., 1995); and underlined by the separate person and process pillars of creativity (Rhodes, 1961).

While both perspectives are useful, their purpose is different. The description of the design process as a series of prescribed activities that will lead to a solution provides a discrete and understandable structure, which can be used and supported for optimisation and management purposes. The description of the design process through the tasks completed by designers gives an accurate representation of the reality of design, what must actually happen in each specific case for a solution to be developed.

It is the relationship between these perspectives that is particularly important. The descriptive method plays a theory building role - through study of a designer's tasks it is possible to develop the understanding necessary to produce largely accurate prescriptive models, which can then be used for management and support. Without descriptive understanding, it would not be possible to prescribe. Conversely, prescriptive models do not accurately represent the step-by-step actions of the designer. A descriptive understanding must be developed before the advantages of prescription can be put into use. This is illustrated in Figure 12.

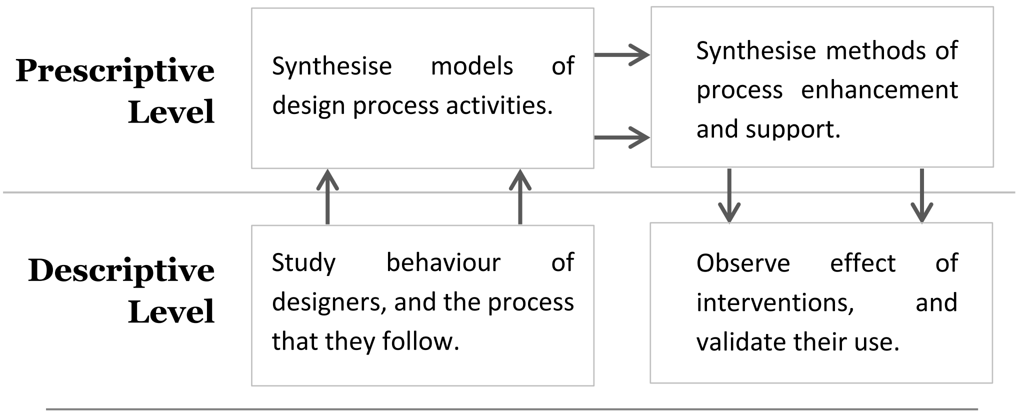


Figure 12: The process of descriptive and prescriptive design research

The implication for design research is significant. When a lack of understanding or theory into a specific part of the design process exists, descriptive study of designer behaviour is necessary. When sufficient understanding and theory exists, it is then possible to form prescriptive models, management systems and support structures to enhance the design process and its output. However, it is still necessary at this point to perform descriptive study of designer behaviour, both to ensure validity of understanding, and to observe the real-life effect of modification and support. This approach closely mirrors research methodologies as proposed in literature and followed in this work, such as the descriptive > prescriptive > descriptive process of DRM (Blessing and Chakrabarti, 2009).

Whether the purpose of research is theory building, model development or designer support, direct observation of designers and their design behaviour is vital. This forms the focus of Chapter 4, which reviews understanding of the behaviour of designers throughout the engineering design process.

3.5.2 The Creative Design Process

There has been considerable work studying the links between engineering design and creativity, and some comparing the general creative process within the general engineering process (such as Howard et al. (2008a). In specific terms, some relationships can be drawn between the engineering design process as described here and the material presented in Chapter 2.

First, an initial part of the research process is to study tasks and behaviour of actual designers through descriptive research, which in turn enables the development of formal models of design. This descriptive study of the actual working of designers can be closely considered from the perspective of creativity. It is through a series of tasks that a designer displays their behaviour, and through creative behaviour that a better solution can be produced. It is therefore also through descriptive observation of designers tasks that a better understanding of creative behaviour and its effect can be found.

Further, activity theory and discussion of descriptive process highlights the individuality of designers working within engineering design. This also links closely to creativity research. A multitude of influences from personality to experience to ability affect the creative behaviour of each designer, both in appearance and extent. Similarly, the individual tasks as followed by designers are liable to vary even within identical activities of the engineering design process. Similar approaches are therefore required for both; using the structure of understanding from the field of creativity it is possible to understand the influences upon a designer within engineering design, which will affect their behavioural process and design output.

There has also been a distinction drawn between early and late stage design in terms of design process influences, focus and situation. In relation to creativity, this distinction begins to approach a primary gap in research (presented in detail in Section 4.5). Typically, creative behaviour is considered to occur within early-stage design; when constraint is lower, time and budget are higher, and focus is on identifying solution principles and system function; and there has been much research to this effect (see Benami, 2002, Eckert et al., 2009, Howard et al., 2008b, Liu et al., 2003). It is a contention of this work however that later stage design is also creative and worthy of this form of study, a view echoed by some of the few who have approached it (see Eckert et al., 2012, Motte et al., 2004b). However, due to the many differences shown in Table 10, assumptions cannot be made to the form of this creativity, or the applicability to the later stages of research into creativity in a general sense or in early stage design.

There is a therefore a need for descriptive research of designers working within later-stage design situations, particularly from the perspective of creativity research. Core to this subject is the study of designer behaviour – the actual tasks that a designer will complete as they progress within a design process. It is this subject that forms the following chapter of this thesis, presenting the understanding of designer behaviour and creative behaviour within engineering design.

Chapter 4: The Behaviour of Designers

A theme throughout the literature researched within this thesis has been the importance of the study of designer behaviour, in contrast to the general activities that designers will complete as part of a design process.

Both the study of creativity and of the formalised engineering design process recognise the importance of the individual, and that variation within processes will always occur due to the role the individual plays. In other words, although study in general terms will provide general findings, specific study of the role of the individual in design is needed for detailed understanding.

Some probable directions for this study have been found. Variation between people is a culmination of their experience, personality and motivation (Section 2.3); creativity within people can be analysed through their style (Section 2.3.6), and variation in process can be result of design situation and design stage (Chapter 3).

This chapter approaches such subjects more directly. Within the field of engineering design and beyond there has been much study of the behaviour of designers, their influences, and the variation between. This study provides many opportunities for study, and significant direction to the research project as a whole.

It is to this end that Chapter 4 proceeds; to present current understanding of designer behaviour within engineering design, and to present the knowledge gap that is addressed throughout the remainder of this thesis.

4.1 Definition of Designer Behaviour

As has been defined in Section 3.2, designer behaviour describes the actions of the designer - the series of tasks that they complete as they develop a solution. This needs to be cumulative study; it is not possible to discern behaviour from a single task. Rather, behaviour is patterns in groups of tasks, culminating to form the way in which designers will complete design activities.

Behaviour therefore reflects reality directly; it is not an abstraction or generalisation of the design process within an area, but the actual series of events that occurred in each specific case of design. Following the understanding of activity theory, it is formally defined as follows:

Behaviour The mental and physical tasks completed by a designer over time, through which individual activities are completed.

The study of designer behaviour primarily concerns the actions level of Activity Theory (Kaptelinin et al., 1995), and complements much descriptive design process research (see Ullman et al., 1988b, Cross, 2004a, Hales, 1986).

The study of behaviour lies deeper than only patterns in tasks completed. Due to the individualistic nature of design, behaviour can be expected to vary between people. As has been described throughout this work, there are a number of potential influences and implications to consider. The study of designer behaviour therefore requires more than analysis of tasks alone, but also understanding of context and influence that may encourage them.

4.1.1 Creative Behaviour

The study of creative behaviour within this work has been described as the study of designer behaviour, as they follow some process to produce a creative product. It then follows that the definition of creative designer behaviour mirrors the definition of designer behaviour, but with a caveat that some properties of their behaviour or tasks allow the result to be interpreted as creative within its domain.

Within the four pillars of creativity (Rhodes, 1961), creative behaviour fits within the creative process. Its appearance can then be indicated in the same way as the creative process, through the appearance of a creative result. As discussed in Section 2.4 however, it can also be indicated through the appearance of exploration within design tasks, manifesting as divergent or creatively convergent behaviour. This is an important point, as it recognises that creative behaviour need not always result in a creative output. Through divergence and creative convergence within a process a designer is able to identify creative solutions, but there is no pre-requisite necessity for these solutions to be chosen.

In all cases when a human designer is part of the process, their personal traits and characteristics will have an influence. These then form a path to understanding – although they may not invariably do so, the traits, characteristics and behaviours of designers who regularly produce creative results can form a focus for research.

In addition to studying designer behaviour in general, this section places emphasis on these thoughts. Through study of behaviour that leads to better results (particularly creative results) within context of the engineering design process, better design behaviours can potentially be identified.

4.1.2 Behaviour and Design Thinking

Within the field of design research, there has been a body of work completed on the concept of design thinking – the forms and sequence of cognitive operations that are employed within an individuals' design process (see Gero, 1998, Finke, 1996, Stempfle and Badke-Schaub, 2002, Goldschmidt, 1994, Lawson, 2006, Goel and Pirolli, 1992). Falling under this over-arching banner are several sections of this chapter, including those on problem framing (Section 4.2.2), problem structure (Section 4.2.3), fixation (Section 4.2.4) and opportunism in design (Section 4.3.3). Considering the body of work completed in the subject, there is a distinction to be made between *behaviour* (as is the subject of analysis within this work) and *cognitive operations* as used within research on design thinking.

Design thinking describes four discrete cognitive operations, through which a designer will solve a design problem (Finke, 1996, Stempfle and Badke-Schaub, 2002); generation and exploration, in which ideas are produced and the solution space is explored; and comparison and selection, in which ideas are compared against one another and a preferable solution is chosen. Through these four cognitive operations, a designer passes through each stage of their design process, applying each when appropriate. For example, in early design process stages the production of potential solution concepts requires exploration of the solution space (as advocated in co-evolutionary theory (Dorst and Cross, 2001)) and generation of solution concepts, following which ideas are compared, evaluated, and chosen between (Stempfle and Badke-Schaub, 2002).

The difference between cognitive process and design behaviour as studied within this work can be clarified through the distinction between internal mental processes and external actions. As per design thinking, cognitive operations are an internal process within the mind of the designer – the series of thought processes through which their actions are completed. It is then through a series of cognitive operations that each designer *task* as defined within this work is completed, and at one further level of abstraction, through a series of designer *tasks* that the design *activity* is completed. There is therefore a significant difference between the study of designer tasks (as occurs within this work) and designer cognitive operations; in simplified terms the former describes *what* the designer does to complete the design activity – the sequence of steps they take), and the latter describes *how* the designer completes their *tasks* – the sequence of mental processes by which they take those steps.

As such, behaviour and cognitive operations are highly inter-linked research topics. The behaviour of a designer can only be truly understood through understanding of the processes internal to the designer that caused them to be completed, and the impact of different cognitive operations can only be understood through their implementation and the impact that each have upon the wider design activity. As such, there is much cross-applicable research on design behaviour and design thinking, as is described throughout this chapter; in order to elucidate understanding research has often focused on not only what a designer will do, but also to try to clarify the internal processes that they were following to do it.

This work presented in this thesis is highly similar in this regard. Throughout, focus is placed on the study of behaviour as a route to understanding of creativity in later-stage design. This is primarily for the reason that the field under study (later-stage creativity) is widely under-studied (see Section 4.5), and as such it is important to understand *what* designers do in relation before it is possible to understand *how* they do it, as would be completed through study of mental process. However, throughout the work completed within this work, many elements that have been studied from the perspective of design thinking are considered, such as a divergent-convergent process (Guilford, 1956, Dym et al., 2005)(see Section 2.4.4), co-evolution (Dorst and Cross, 2001, Maher and Poon, 1995)(see Section 4.3.2), reflective practice (Schon, 1983)(see Section 4.2.2), and problem structuring (Simon, 1973) (see Section 4.2.3). As a result, this thesis bases its study of later-stage behaviour upon widely researched understanding of design thinking and its relationship to behaviour in a more general context, and as such grounds its understanding gained within current understanding of designer mental processes. While it is not the primary subject of this work to study cognitive operations within later-stage design (a subject which forms part of the potential for future work that this thesis provides), through understanding of design thinking and its relationship to the behaviours observed, this thesis maintains compatibility with the wide body of work completed by others.

4.2 Characteristics of Designer Behaviour

As a rather broad topic that can be approached from both design related fields and from psychology (Howard et al., 2008a), the study of designer behaviour has received much attention within literature.

One common approach is through the study of designer expertise, also termed expert performance, relating to the process that a person follows which leads to a result that is recognised as exceptional (Ericsson, 1996). In this way its study closely mirrors the approach taken within this work – it is not the result that is the key, but the way in which the result was reached. Through such study it is possible to build a detailed descriptive account of the actual process that a designer will complete, which can then be used to developed prescriptive understanding, effective education and methods of designer management and support.

Following the theme of creativity as introducing a result that is in some way better than its peers, this section generally takes the perspective of expertise and expert behaviour as denoting a substantive difference in behaviour from the norm, and that should reflect better practice. Better practice is here defined by as a classification of designer behaviour, which leads to a better result according to relevant measurement criteria. The study of how better practice is achieved should then provide useful potential directions for research.

4.2.1 Expertise

The study of expertise has proven a major subject of research in its own right, particularly in the field of psychology.

Key to its acquisition is consistent deliberate practice within a field (Ericsson et al., 1993, Simon and Chase, 1973), requiring both a high level of motivation (Lawson, 1994, Ericsson, 1996) and the ability to circumvent constraints that inhibit performance in less-experienced individuals (Ericsson and Lehmann, 1996). As time passes, so will performance of the expert improve within the context of their domain of practice (Voss et al., 1983, Chi, 2006), resulting in characteristics such as improved pattern recognition (Simon and Chase, 1973) improved memory recall abilities (Ericsson and Lehmann, 1996), selection of solution strategies (Chi, 2006), and accurate self-monitoring of work and errors (Chi, 2006). It is generally accepted within literature that the time to reach expertise is ten years from first practice (Ericsson, 1996). A close tie can be made here to the role of practice in creative ability, as made in Section 2.3, in that to display creative ability also requires significant practice in the field.

These thoughts also highlight the important difference between experience and expertise. In the former, a person is highly familiar with the subject matter, in the latter, a person is capable of consistently producing good results. As stated by Ericsson (1996), Ericsson et al. (1993), experience in a field does not preclude high performance (and hence does not preclude expertise); it is only through deliberate practice and training that expert levels of performance can be reached. The level of experience and expertise of a person can then be thought of as according to three individual categories: unexperienced, where a person has no experience of a field; experienced, where a person is familiar with a field but does not necessarily display expert performance; and expert, where a person demonstrates high performance within their field of experience as a result of deliberate practice within it. As used within the field, the term novice in this work refers to a person with little or no experience, and therefore someone from whom expert performance cannot be expected. The term non-expert is used within this work to represent a designer who is not expected to display expert performance, but does not hold connotations to the quantity of their experience.

It is interesting to consider the difference between the actual actions of experts in comparison to non-experts and the differences in results. As demonstrated, both in and out of the field of engineering, the difference between experts and non-experts is not necessarily through actions, but rather due to skills realised through extensive practice. For example, within chess there is no difference between world-class players and club players in the amount of and depth of searching for moves (de Groot, 1978, Ericsson and Lehmann, 1996). Evidence has suggested that the difference in skill (as recognised by selection of stronger moves) is instead due to experts recalling good moves from memory, and thereby a result of pattern recognition, while non-expert players must complete a more general search strategy (Simon and Chase, 1973, Jansch and Birkhofer, 2007). Within engineering, there has also been evidence of little difference between the core design activity of experts and less-experienced engineers (Cash et al., 2013). Making a link to expertise research then suggests that experts are better not because they follow a different process, but rather because they remember and follow the better moves more efficiently.

A common aspect that is noted as one reason for the superiority of experts is that of the wealth of knowledge that they possess (Jansch and Birkhofer, 2007, Ericsson, 1996). While the extent of knowledge on which experts draw may not always be positive (as explored below), it allows them to follow certain patterns of behaviour that are not available to the novice designer. As noted by Ahmed (2003) and Cross (2004b), while novices will progress with their design to a stage of implementation before evaluating its quality, experts will consistently evaluate as they work. These consistent evaluations allow the expert designer to progress in a direction that is more likely to prove feasible and appropriate, eliminating the dead ends that many novices may follow; and also allows the expert designer to consider many different alternatives in a shorter space of time, with each requiring less work before evaluation can take place. This recognition of patterns allows the design process to become more reasoned, based on likely appropriate outcomes rather than the far more iterative, often ‘trial and error’ approach of novices (Ahmed et al., 2003). Another aspect of expertise and knowledge is the structure of its storage. Through abstract concepts that can easily be adapted and applied, experts are able to recognise, understand and proceed in an effective manner with a reduced cognitive load in comparison to novices (Ericsson, 1996, Chi, 2006).

An extension of this evaluation is the ability of designers to consider multiple aspects of the process simultaneously. While novices will separate their process into largely discrete stages

(Seitamaa-Hakkarainen and Hakkarainen, 2001) through which they can individually work, experts have the ability to work on different levels in parallel, considering multiple levels of detail, technical and visual elements (Lawson, 1994, Ahmed et al., 2003, Seitamaa-Hakkarainen and Hakkarainen, 2001). Perhaps due to the lower level of cognitive loading required due to the knowledge and experience that the designer already holds, this process of parallel thinking allows them to consider both a higher quantity of options and a higher level of detail within. Consequently, this may be another explanation for the ability of experts to progress in a more reasoned manner, in which the high level of detail and cross-consideration of many separate elements allows them to make an informed analysis of the product and evaluate its feasibility or appropriateness.

The limits of expertise

Two of the key aspects of expertise have been described as knowledge and the ability to recognise methods of using knowledge in a particular situation. However, the relationship between expertise and performance is more complex.

Foremost is that expertise is a highly domain dependent phenomenon (Voss et al., 1983, Ericsson et al., 1993). One who is expert in a certain field of design will not necessarily be able to natively achieve expert performance in another without the same training as any novice, and certainly not if their second area of application shares little knowledge with the first. Better practice is built from experience in a certain field and the knowledge required to effectively follow probable successful processes within. Once outside of that field, a designer will not have the ability to recognise the design situation and method to proceed, nor the knowledge to quickly evaluate and select strong solution candidates.

A second consideration is in the role of deliberate practice within the acquisition of expertise; a matter that to some extent accounts for the individual difference between experts in similar fields and of similar experience. In reality, the level of performance between experts and novices can be surprisingly similar (Ericsson, 1996); as example, Simon and Chase (1973) noted that both amateur and expert chess players would choose the same strong solutions for their moves, it would just take the expert less time. According to Ericsson (1996), Ericsson et al. (1993), the reason for this is in deliberate practice aimed towards improving skills and abilities. Even at the upper echelons of performance, there is a dramatic difference in the amount of time given to improving abilities (Figure 13; showing the accumulated hours deliberate practice against level of performance of musicians), and it is this time for improvement that is thought to lead to consistently high performance; not simply immersion in a field.

The implication of this is in placing the study of expertise in perspective. While the study of those who have been within a field for a number of years may logically indicate higher performance, there is no necessity for it to do so. Expert performance is highly domain-dependent (Voss et al., 1983) and task-specific (Bonner and Lewis, 1990), giving potential for many cases in which a relative novice also produces excellent results. In research, it is both necessary to in part temper focus away from purely expert performance and consider the processes of non-experts, and also to consider the wider context and domain in which the expert is working.

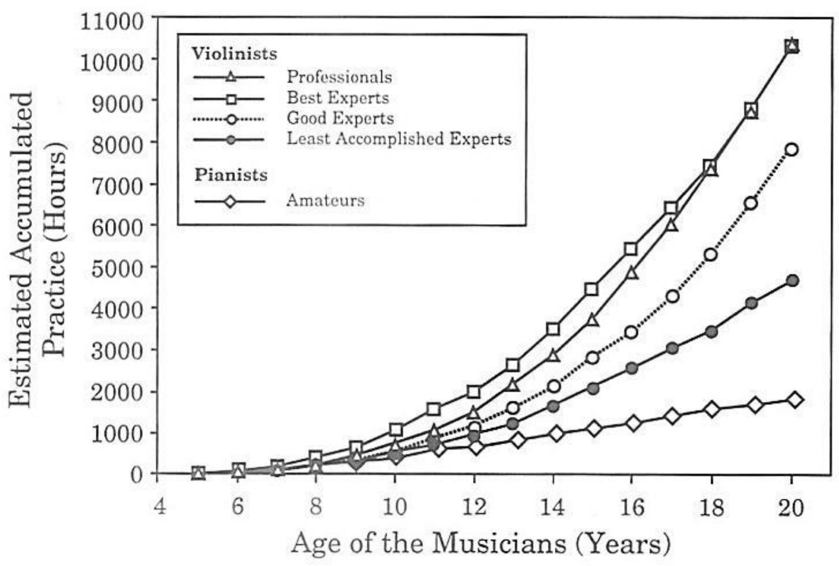


Figure 13: Deliberate practice in the acquisition of expert performance (Ericsson et al., 1993)

4.2.2 Problem Framing

The way in which a designer views a problem is a highly important part of the design process. It is through their understanding of the problem, the primary influences upon it, and also the principles by which the problem should be solved that any designer will proceed. As proposed by Schon (1983), this *frame* acts as a base perspective on a design problem that provides the means to understand the intricacy and nuance of the requirements and opportunities that appear within design, and that through a reflective process this frame can be re-evaluated and evolve to allow the production of viable solutions.

With each designer, the frame that will be used will vary. Even within domains, there are a number of ways in which a problem can be considered, and the choice of which shall be given priority is very much down to the experience and knowledge of the designer (Schon, 1983). While one may take a requirement specification and consider it from the perspective of a manufacturing engineer, another may consider minimisation of cost to be the main concern, or maximal sustainability, or even branding and place within the market. In each case, the frame of reference of the designer provides cues that lead towards a solution; the manufacturing engineer towards current capability and ease of manufacture, the costing engineer towards a design that minimises material waste, the marketing team towards a design that fits within the brand identity.

It is then worth looking then at the effect of the frame of reference of the designer on the production of a creative outcome, and at the way in which expert designers will frame their problem when compared to non-experts. Tying closely with the concept of the creative leap of Wallas (1926)(Section 2.4), one conclusion that has been made regards the necessity of the breaking of a frame of reference in order to produce a creative solution (Akin and Akin, 1996). As such, it emphasises the importance of change in the way that things are done in order to produce novelty, or a change in the perception of the designer to allow them to see the options available to them. This then ties closely with the view of creativity of Gero (1996) as requiring either a new variable or a new perspective on the problem to allow novelty to appear; as well as the views of Moreau and Dahl (2005) who state that for creativity to appear the designer must be forced away from their "*Path of Least Resistance*" through the introduction of constraints that are incompatible with their frame of reference.

Considering then that taking a "standard" frame of reference (in which the designer is viewing the project from a perspective that is highly influenced by their past experiences, previous products and expectations of the solution) increases the possibility of a non-creative result, the study of how creative designers frame their problem may provide insight into how creativity may be stimulated. This assumption has been demonstrated in practice through the study of idea generation. When tasked with generating ideas that are based on familiar concepts, designer produce less novel solutions than when primed to generate ideas based on unusual concepts (Ward et al., 2004), or even when forced to take an unusual perspective (Finke, 1995, Finke, 1990); and when primed by specific examples, designers will produce solutions that can easily be traced back to them (Ward, 1994). Two observed practices of expert behaviour that counteract the influencing effect of familiar framing are that of framing from a fundamental perspective, and framing as an ill-structured problem; the latter of which is discussed in Section 4.3.

As observed by Cross (2004a) when studying the behaviour of three highly eminent designers, all framed the problem not from their own experiences, but from the first principles that govern it. For example, when designing a bicycle rack to be placed over a rear wheel, the designer did not consider the shape of the bike and how it may accommodate a rack, or the shape of loads that the rack must hold, or the use that the rack would get. Instead, he identified the forces that the load may generate, and designed a structure that would support the resulting force pathways in a highly stable and secure manner. This was then subsequently adjusted to fit the bike, in what can be interpreted as the reflective process proposed by Schon (1983). By developing a solution directly from the first principles that govern the function of the product (in this case the forces applied) the designer placed many of the requirements of the rack as secondary, and was able to find a functionally sound solution that could then be adapted to its application. By framing the priority of the approach as through force pathways and analysis, the designer steered away from pre-conceived notions of the form that a bike rack should take, allowing the production of a more novel solution. In essence, the designer created a contradiction between the focus of their development process and the focus of the main requirements to which they had to adhere. Similarly, Jansch (2007) noted that experts will not base a design on its physical elements, rather looking at the function, purpose or fundamental principles on which it was built. This has a similar effect; the designer is not influenced by suggestions of the form that the solution should take or would usually take, and instead builds a solution from the fundamental elements that will ensure it will work.

The effect of the expert designer is then in the knowledge and experience that they hold, and in the manner in which they frame a problem. Through the ability to recognise a design situation as one that they have experienced before, expert design behaviour will be evident through the subject of focus in their design process; whether they concentrate on first principles, geometry, or any number of others. By linking to existing understanding, the expert designer can form a frame that they know will not fail to develop a viable solution. Additionally, by framing a problem in a manner that is not usual, or that does not rely on pre-conceived notions of the solution, a designer can encourage the production of a solution that would be interpreted as original – hence closer to one that could be classed as creative.

4.2.3 Problem Structure

The notion of problem structure describes two basic forms (Simon, 1973). Within a well-structured problem there is a defined space by which the problem can be described, which contains all required information, all possible solution stratagems, and the desired goal state. Within an ill-structured problem the problem space is simply too large, complex or ill-defined for all possible solutions to be considered. In reality, the difference between well and ill-structured problems is more complex; due to the breadth of options and complexities of solving any problem, there are few that can truly be described completely in terms of their end point, their initial state, all state transformations that can occur, all knowledge available and relevant, and all possible end state permutations. Similarly, all level of structure is therefore relative in terms of what is known of each, through truly exceptional computational effort many ill-structured problems could become well-structured (Simon, 1973). In essence, however, definition through problem structure allows any problem to be described as according to the problem space in which it resides, and the extent to which the problem space is detailed and understood. This notion of problem structured-ness has been broadly studied (see Simon, 1973, Ge and Land, 2004, Jonassen, 1997, Dorst, 2006).

Design itself is fundamentally an ill-structured problem (Simon, 1973, Dorst, 2003, Jonassen, 2000); there are a multitude of different possibilities both within the method for approaching a design problem, and for the form that a solution may take. Depending on elements such as frame of reference, past knowledge and experience, and priority given to different functions and requirements a designer may produce a multitude of viable solutions; in reality there are too many alternatives for the problem space to be fully defined. However, given such aspects as past experience, existing methods and design processes, it is possible that in many cases a designer will actually know the route to solution for a given problem. The entirety of the problem space is not understood, but it is understood to a sufficient extent for the expert to recognise a path to a solution. Although ill-structured in principle, a designer is able to treat such situations as if they were well-structured, and therefore has a direct and clear path to solution.

Given that this would allow a designer to easily pass through the design process, likely quicker and more efficiently than would be possible if they did not know a path to solution, it is perhaps surprising that many researchers have identified expert designers as treating a problem as if it were ill-structured, even when a well-structured problem space exists (Cross and Cross, 1998, Holyoak, 1991, Thomas and Carroll, 1979, Candy and Edmonds, 1997).

Taking for the moment the assumption that expert behaviour reflects better practice, this would suggest that the framing of the problem as ill-structured will produce a better result. Certainly, following the prescribed or expected path to the expected solution will likely not lead to originality, and therefore makes a creative result less likely. Within Section 2.4, creativity was defined through a lack of variables and knowledge for design (or a lack of knowledge of how to use them) (Dym, 1994, Gero, 1996), which also shows similarity to the thought of a lack of problem structure leading to a creative result. Even when a solution exists and is known, or when a significant amount of information regarding a solution is present, behaving as if solving an ill-defined problem will allow the designer to produce unexpected solutions, that may bare excellent features or benefit that the “well-structured” approach would not.

4.2.4 Fixation

A curious observation of designers within any design process is that of fixation; even when better solutions are found, designers are often reluctant to abandon their original solution conjecture and adopt the new. In many cases, despite the range of solutions that are possible, designers will find it difficult to see the options that are available to them; instead focussing only the well-known functions, the solutions that already exist, or the initial ideas that they develop (Purcell and Gero, 1996, Cross, 2001).

This effect has been found in multiple experiments (Jansson and Smith, 1991, Ward et al., 2004, Linsey et al., 2010, Ward, 1994), and is considered a barrier to creativity, in which the designer imposes constraints on the possible solution that need not be present. Avoiding fixation is even classed as a characteristic of the creative person, judged through the "*resistance to premature closing*" category of the Torrance Tests for Creative Thinking (Torrance, 1998). As a reaction, some research has undertaken the task of identifying methods of de-fixating designers through the use of instructions or examples (Chrysikou and Weisberg, 2005), re-framing in a manner that does not fixate (Linsey et al., 2010), or physical prototypes (Youmans, 2011).

This trend is not experience-independent, appearing in both novice (see Chrysikou and Weisberg, 2005, Jansson and Smith, 1991) and expert behaviour (Chi, 2006). In both cases, it appears that knowledge and experience are the root cause of difficulty. Particularly within expert behaviour, for any given problem there is likely a large repository of methods and solutions that the designer has experienced in the past, and through which the designer knows they may be able to develop new solutions. They then tend towards inflexibility in their process due to this knowledge (Chi, 2006, Jansch and Birkhofer, 2007), perhaps explained through the path-of-least-resistance model (Ward, 1994, Ward et al., 2000). This states that when a new problem appears, a designer is more likely to attempt to solve it through exemplars from the domain with which they are already familiar due to the lower difficulty involved. Such a case would then hold parallels to cognitive load theory (de Jong, 2010), in that designers will use past examples to minimise the cognitive load that the design process requires. When considering novices, as with experts, there is evidence of the frequent use of exemplars formed from examples given or from past, unrelated experiences (Ward et al., 2000, Chrysikou and Weisberg, 2005).

With particular consideration of creativity in design, one can imagine scenarios in which fixation is either bad or good. Although, as studied by several, the notion of fixation describes a narrowing of the design process to the examples given or past experiences (Agogue et al., 2011, Chrysikou and Weisberg, 2005), it is equally possible that positive fixation towards particularly beneficial features or highly original concepts will encourage a better outcome (Jansson and Smith, 1991). As an abstracted example, parallels can be drawn between the resistance of fixation and the use by expert designers of ill-structured problems. To resist fixation requires the designer to see alternatives that may exist and may benefit the solution, passing over their preconceived notions of what is possible or what should be done. Similarly, the framing of a problem as ill-structured requires the designer to perform significant exploration in order to develop a solution, studying both the problem that has been set and the various solutions that may be possible. Through ill-structured problems the designer is preventing fixation from occurring; such a problem has no clear solution, and provides the designer with little concrete information by which they may proceed.

4.3 Designer Solution Strategy

Section 4.2 has described some of the primary characteristics of expert behaviour within the design process. In a similar manner, research has also been conducted specifically into the behavioural process followed by designers; that is the actual sequence of actions designers complete and patterns within, rather than the discrete design process activities described by many models. This section describes patterns found within the process of designer behaviour, again with a focus on that completed by experts.

4.3.1 Solution Strategies

The previous chapter has already implied some solution strategies that experts will follow. For example, during their framing process experts have a tendency to consistently evaluate and re-frame their problem so that it will lead to a stronger solution, referred to by Schon (1983) as reflective practice; or attempt to force a problem to ill-structure (Cross and Cross, 1998), perhaps leading to better results.

Further to these, some researchers have explicitly studied the solution strategies of designers. For example, Ball et al. (1997) demonstrated that experts follow a primarily top-down and breadth-first strategy, with forays into depth when clarification or detail is needed. This is represented in the process by widely completing design for an entire system in general terms first, and then moving through subsequent levels of system hierarchy while keeping the completion of each sub-system approximately equivalent. When needed, the designer will go into significant depth on a specific sub-system or component, should it inform the design of systems at a higher level.

Others have noted the solution-focused nature of design (Ho, 2001, Lloyd and Scott, 1994), in which designers form initial solution conjectures which are altered through the design process to meet the requirements of the problem. This closely links to the solution-focused nature of engineering design as a whole (Lawson, 2006), in which designers are highly focused on the practicality of design rather than detailed interpretation and forming of the problem.

4.3.2 Co-Evolution within Design Processes

Tying the observations of many researchers of design process behaviour together is the concept of design as co-evolution of a problem space and a solution space, which both grow through an iterative process of generation and evaluation (Maher, 2000, Dorst and Cross, 2001, Poon and Maher, 1997, Smulders et al., 2009). This theory states that in any design process a designer will produce a primitive solution conjecture based on the problem statement. They then evaluate this conjecture against the original specification, learn from the implications and deficiencies, and form a new solution conjecture based upon the understanding gained from the last. This process is shown in Figure 14, where the initial problem statement *P(t)* is transformed into a solution conjecture *S(t)*; which is then used as a basis for assessment to re-iterate and develop the initial problem statement into *P(t+1)*. A new solution conjecture is formed from this point, and the process continues until a suitable solution has been found.

Parallels and evidence to this thinking can be seen in much research. For example, Schon (1983) comments on the reflective nature of a designer in reviewing the implications of their current design frame, and acting upon them to form an evolved, more viable (and often more beneficial) version. In his Function-Behaviour-Structure (FBS) model of design, Gero (1990) describes much of the design process as an iteration between the behaviour that the current solution conjecture holds, and the expected behaviour of an ideal solution. Lloyd and Scott (1994) observed repetitions of solution generation and evaluation as central to the design process, particularly within expert behaviour; while more recent research as provided evidence for co-evolution directly (Dorst and Cross, 2001, Smulders et al., 2009, Wiltschnig et al., 2013).

Considering design as a co-evolutionary approach demonstrates a need for flexibility. In order to produce a solution, a designer will frequently evaluate their solution against requirement, using this process to learn and understand the problem in higher detail. From this step they are then able to revise their solution to be better than before, changing aspects that violated constraints or important conditions and altering the solution principle to better match the requirements of the problem.

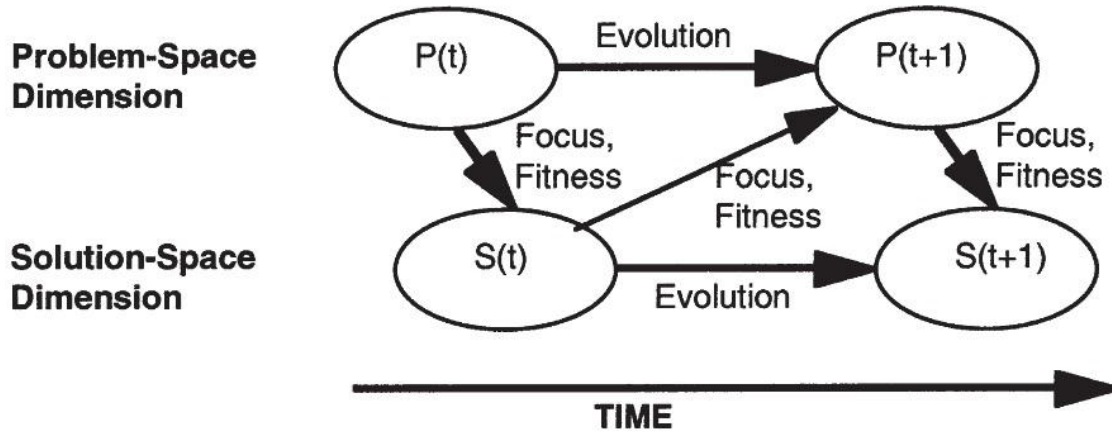


Figure 14: The co-evolutionary design process, (Dorst and Cross, 2001)

Co-evolution describes the fundamental behaviour through which a designer proceeds. Through a process of generation and evaluation, a designer will produce increasingly detailed and viable solutions to a design problem, until the point at which the current solution conjecture matches what is needed from the output.

4.3.3 Opportunism within Design

While the models of design may seem to advocate a structured and procedural approach, one observed feature of designer behaviour is that of opportunism, seen in the way in which designers will jump from one area of focus to another (Cross, 2001, Radcliffe and Lee, 1989, Guindon, 1990, Visser, 1990, Visser, 2006). Originally termed by Hayes-Roth and Hayes-Roth (1979) (cf. Bender and Blessing, 2004), opportunism relates to the way in which specialists progress through the process via the areas that they view as providing opportunity, rather than in a particularly structured or linear manner.

As they pass through the design process, opportunism appears through a variety of levels of abstraction, decomposing problems not through a systematic structure from the highest level to the lowest or a linear structure from early tasks to late, but rather through the information and requirements present (Guindon, 1990). When a new partial solution or requirement comes to light, the designer may transfer focus to an alternative design level, system or design stage in order to apply it or develop its implications, rather than maintaining focus on the task that was previously being completed. This is reinforced by Visser (1994) in relation to design project planning, who concluded that despite the knowledge of a pre-existing plan, an expert designer will often follow a separate approach that they viewed as an opportunity, even when a routine option exists and is known. Visser states that the important factor that creates this deviation is based on the cognitive economy, in which the designer will stick to the plan only if it is of lower cognitive cost (requires less thought, or is viewed as easier) in comparison to the opportunistic alternative.

In support of this view, a study by Bender and Blessing (2004) found the superiority in the opportunistic process, with designers who employed one producing better results than those who followed more typical hierarchical models. Figure 15 shows a higher median performance of "*opportunistic and associative*" design than any other assessed category. Particularly of note is that this category scores above the design-process-mirroring "*hierarchically phase-oriented*" category.

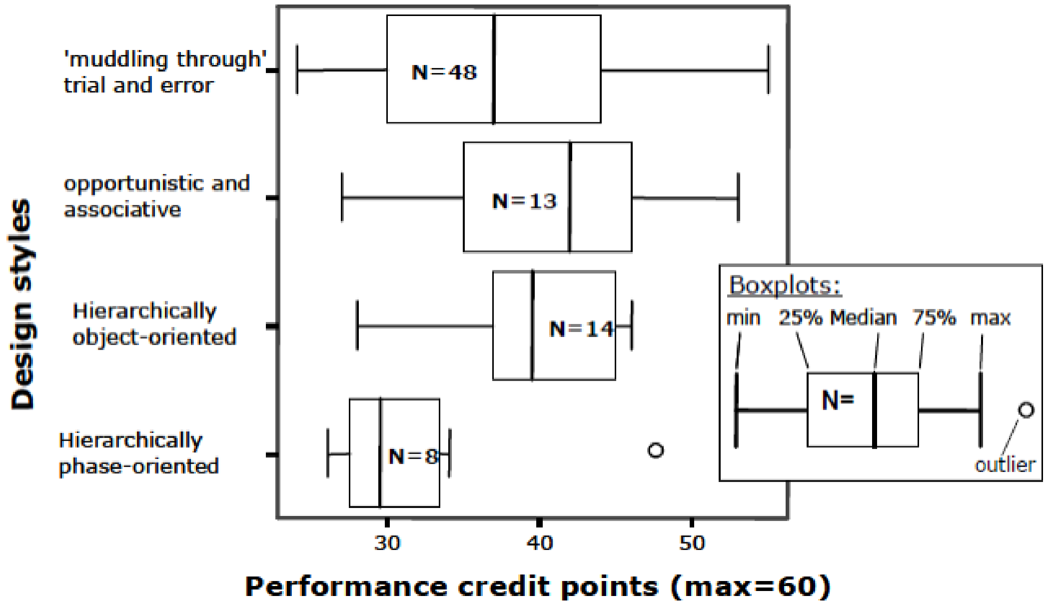


Figure 15: The superiority of the opportunistic process (Bender and Blessing, 2004)

Opportunism perhaps demonstrates a role of past experience and knowledge within design. Those who are particularly practiced in a field will hold a wider repository of potentially relevant information throughout the process. As the design develops, they are perhaps able to make connections with their current work and past examples from their experience, which present opportunities for improving the product (such as performance increases). It is then beneficial for the designer to consider opportunities throughout the entirety of the process, and to maintain flexibility in order to enact them.

4.4 Design Behaviour and Creativity

In addition to study of designer behaviour, some researchers have specifically studied creative behaviour within the design process. This research is often highly informed by study of design behaviour in general, from the context of that which encourages a creative solution.

As discussed in Section 4.2, problem framing describes one difference between expert and novice designers and states that an expert designer will select a frame that encourages a better solution to be found. This thinking is extended to creative behaviour by Cross (2001), who proposes that a change in frame is required for a creative solution to come to be. Looking at particularly creative designers (Cross, 2004a), this occurs not through an active assessment of problem frame at some point in the process, but rather by selecting a distinctive problem frame at the outset, changed as it were from the problem frame that would typically be selected for such a problem. It is the initial conditions set by the frame that then cause the encouragement of creative behaviour throughout.

This ties closely to study of ill-structured design problems. Also recognised as a feature of expert behaviour (Candy and Edmonds, 1997, Cross, 2004b), the preference for ill-structured problems even when a well-structured approach is known could be taken as representative of designers forcing exploration (divergence). When ill-structured, some form of exploration of variables involved in the design and the knowledge and resources available is necessary in order to form a solution. As a result, creative behaviour by the definitions within this work is also required (see Gero (1996) and Dym (1994)). This selection of an ill-structured approach could be instigated through a problem frame that forces exploration by the expert. Findings to this effect can be found in Cross (2004a) who noted creative designers forming their problem in such a way that it required solution through first principles to solve.

Another strong link between designer behaviour and creative behaviour relates to the co-evolutionary design process (Dorst and Cross, 2001, Maher and de Silva Garza, 2006), Section 4.3. In this work, the point at which a creative solution appears is described as the forming of a creative bridge between the problem space and solution space, which allows designers to build upon it to form a solution. They describe the creative process initially as an exploration of the problem, checked against criteria based on the experience of the designer. Concurrently, the designer sorts through this information to find interesting or surprising points, based on their personal experience and knowledge, which they note. At some point during this process these interesting or surprising points coalesce into a structure that can be used for solution, in much the same way as a creative leap is thought to appear in the creative process (Akin and Akin, 1996, Wallas, 1926). This structure then acts as a base upon which the designer works, used as a bridge between problem and solution space in order to produce a creative product.

This process says two things about creative behaviour. First, as has been claimed at numerous points throughout these chapters, is the requirement for exploration in order to develop a creative solution. The second point discusses the role played by experience and individuality of the designer. The process of selecting interesting or surprising points is highly based on each individual designer, what they know to exist, and what they know to be useful. From this information, they are able to steer their design process in a direction that will lead to higher originality and effectiveness in solution. This filtering process acts as the difference between expert and less-experienced designers; all designers are capable of exploration, but it is the knowledge and experience of experts that more frequently leads them towards original and effective solutions.

4.4.1 Creative Behaviour and Constraint

In recent years, a growing body of research has studied the role of constraints in the generation of creative results. Considering the focus on later-stage design within this work, in which levels of constraint are higher (Howard et al., 2011, McGinnis and Ullman, 1990), this is a particularly interesting subject.

There are conflicting views in literature on the way in which constraints influence the appearance of a creative result (Amabile, 1996). While some argue that the role they play is more inhibitive (see Matthews et al. (2002)), others suggest the opposite; that through the manipulation of constraints it is possible to encourage a creative outcome (Moreau and Dahl, 2005, Stokes, 2007). It is thought to be important to strike a balance between an open and closed design process (Onarheim and Wiltschnig, 2010), on the one hand providing a design space in which the designer can explore, and on the other providing adequate constraint to give direction. The role of constraint could perhaps be seen as another method by which the designer creates an ill-structured design problem, restricting development away from non-creative solutions and towards ones that are more original. For example, Stokes (2007), Stokes (2009), Stokes (2006) claims that a creative solution comes from the use of constraint pairs; the first of which limits the design space away from the direction that is commonly taken, and the second of which promotes a related but new direction. In this way the designer purposely constrains their process away from what they know is not original, and also purposely creates a direction towards what they know is. This active process ensures originality in outcome, through the individual knowledge and choices of the designer.

4.5 A Knowledge Gap: Late-stage Design Behaviour

As demonstrated by literature concerning creative behaviour and the engineering design process, significant variations occur between designers. In terms of creativity, factors such as creative style, personality, experience, and ability will impact the behaviour that the designer displays (Section 2.3). In terms of the design process, similar factors will also cause variation in the behaviour between designers at identical stages, whether the behaviour is creative or not.

This thinking is extended when variation in the design process itself is considered. First, the design process changes in many ways as it progresses (see Table 10), such as in focus, constraint, complexity, and external influencers. As a result the required behaviour of designers, and indeed the behaviour that designers will display, may vary significantly as the process continues. Secondly, as designers are under influence of the conditions of their design situation, their behavioural patterns may change as the design process continues. In other words, the way in which a designer needs to behave in order to find a solution might change, as might the fundamental ways in which they are able to behave.

For these reasons, designer behaviour must be studied in context of the stages of the design process at which it occurs.

4.5.1 Early and Late-Stage Designer Behaviour

Particularly of interest are then any behavioural differences between early and late stage design.

When reviewing literature, it is clear that this subject has received little attention. Much research looks at design behaviour in a general sense within the design process, some of which will be relevant to later-stage design, but does not make any analysis directly along this thinking. A smaller body of research considers designer behaviour in early stage design. While this research can be placed in contrast to later-stages, without explicitly study of later-stages no conclusions can be made. As shown in Table 11, later-stage design has received little attention. Note that in this table, the first two columns present a small cross-section of available research, while the final column presents the culmination of exhaustive search and, even so, some of the work within is not directly relevant.

A summary of the research within the "Late-stage Design" column of Table 11 is given in Section 4.5.3.

Table 11: Literature on design behaviour within the design process

General Process	Early-stage Design	Late-stage Design
(Ball et al., 1997)	(Schon, 1983)	(Bender and Blessing, 2004)
(Dorst and Cross, 2001)	(Ward, 1994, Ward et al., 2004)	(Motte et al., 2004b, Motte et al., 2004a, Motte and Bjärnemo, 2004)
(Smulders et al., 2009)	(Cross, 2004a)	(Eisentraut, 1997)
(Cross, 2004b)	(Björklund, 2013)	(Feng et al., 1996)
(Fricke, 1996)	(Goel and Pirolli, 1992)	(Scaravetti et al., 2006)
(Hales, 1987)	(Guindon, 1990)	(Matthiesen, 2011)
(Ullman et al., 1988b)	(Liikkanen and Perttula, 2009)	
(Cash et al., 2013)	(Yilmaz and Seifert, 2011)	
(Ahmed et al., 2003)	(Gero, 1998)	
(Atman et al., 1999)		
(Radcliffe and Lee, 1989)		
(Schon, 1983)		
(Kruger and Cross, 2006)		
(Gero, 1990)		

The literature demonstrates a knowledge gap in the area of late-stage design behaviour. Much valuable research has been performed with regard to all other aspects of the design process; there is also much to gain from study of late-stage designer behaviour explicitly.

4.5.2 Early and Late-Stage Creative Behaviour

Through the previous chapters, study into creative behaviour has been shown to have much relevance and similarity to study of designer behaviour in engineering design. Creativity as a research field provides understanding that can be applied to engineering design. It is also then interesting to consider the study of creativity and creative behaviour with context of the stages of the design process.

In this more specific area there are even fewer examples of study directly related to later-stage design. As with Table 11, Table 12 shows a cross-section of relevant research within the first two columns, while the third shows the results of exhaustive search. Only one paper has been found concerning creative behaviour in later-stage engineering design.

This fact reinforces that a knowledge gap concerning later-stage design exists. Further, through the study of creative behaviour, which leads to a better result by definition, there is scope to provide significant benefit from specific research.

Table 12: Literature on creative design behaviour within the design process

General Process	Early-stage Design	Later-stage Design
(Akin and Akin, 1996)	(Cross, 2004a, Cross, 1997)	(Eckert et al., 2012)
(Christiaans and Venselaar, 2005)	(Chan et al., 2011)	
(Demirkan and Afacan, 2012)	(Adler and Obstfeld, 2007)	
(Dorst and Cross, 2001)	(Benami, 2002)	
(Gero, 1996)	(Carayannis and Coleman, 2005)	
(Howard et al., 2008a)	(Eckert et al., 2009)	
(Ward et al., 2004)	(Nguyen and Shanks, 2009)	
(Maher and de Silva Garza, 2006)		

4.5.3 A Summary of Late-Stage Research

The lack of research into later-stage design behaviour has been noted by a small number of researchers in the past few years (see Motte et al. (2004b); Matthiesen (2011); Feng et al. (1996)). However, the small body of research that exists does provide understanding.

First, there is a comment to be made about the placement of researchers within Table 11. Some, (such as Ahmed et al. (2003) and Gero (1990)) make no distinction to early and late-stage relevance of their results, and in truth do likely present findings that are useful within the context of this work. However, as they do not make such distinctions, it is difficult to explicitly infer those findings to apply, and those to investigate. For this reason, such research forms part of the fundamental research that informs the project as a whole.

There is also a comment to be made about the relevance of the references presented as concerning the later-stages of design, some of which represent consideration of later-stage design, but do not share a research focus. Eisentraut (1997) does not specify later-stage design in their work, but by the nature of the task and the work that the participants completed, it does largely concern it. Feng et al. (1996) recognise that the later-stages require research, but provide a representation method rather than study behaviour. Scaravetti et al. (2006) do study later-stage design process, but from a perspective of computerised automation rather than designer behaviour. This is actually a more common subject within literature, but does not directly compare to the knowledge gap.

There are therefore few remaining examples of work of direct relevance.

A series of conference papers published by Motte and Bjarnemo (2004) and Motte *et al.* (2004a, 2004b) concerned firstly the lack of research relevant to later stage design considering cognitive aspects of the designer (of which they found no relevant example); and second addressed this need through the development of a coding scheme that modelled the designers cognitive process.

Through this method, Motte produces some very interesting conclusions relating to the processes that the designer follows within the later-stages of the design process.

- During the later-stages of the design process, designers spend far less time considering the problem, both in terms of determining specific information that may help them to develop a better understanding, and in terms of re-formulating the problem itself. This process is far more common in conceptual design and is considered a common and important part of the engineering design process.

- Solution generation occurs through a process of synthesis of mechanical models, followed by dimensioning and then evaluation, before iteration of the same. In each case the solution is generally complete, and is developed through a combination of designer experience and creative illumination, in line with the theory of Wallas (1926).
- The act of detail drawing is a control within later-stages, due to the need for all specifications to be present within it. When the designer encounters an aspect for which they have no solution at this point, they return to solution development.

This work shows the different emphasis that is placed on the later stages when compared to the early. Although engineering designers tend to be solution focused (Lawson, 2006), the early stages promote development of the problem as well as the solution (see Schon (1983), and the development of information that may re-formulate the way the problem is viewed. In the later stages designers will accept the problem as-is, and attempt to develop a solution directly. Perhaps due to the higher level of definition and constraint present during these stages (Howard et al., 2011, McGinnis and Ullman, 1990) providing a clearer path to a potential solution, this is thought unlikely to be of benefit creatively. Should the designer fully accept the conditions of the problem at later-stages, they are less likely to diverge, converge creatively, or explore.

What is not explicitly considered within the work of Motte is the role of creativity. Despite its mention as important, Motte goes into little detail of the occurrence of creativity, how it may be stimulated, or the role that it may play within the later stage design. What he does say however is that it creative actions do occur, a conclusion more recently drawn by other researchers (Howard et al., 2011, Eckert et al., 2012). Although it is not clear from where this conclusion comes, it follows thinking within this work.

Another study that has concerned designer behaviour and process within later-stage design is that of Bender and Blessing (2004), although it must be said that due to the lack of definition of what is meant by embodiment, this work may in truth concern very early embodiment or conceptual stages. In brief, it surmises that the best process to follow within embodiment is not step-by-step, but rather to change the area of focus to whichever provides the best opportunity. This is similar in suggestion to research into opportunism (Guindon, 1990, Visser, 1994), with evidence that the opportunistic process is indeed in these stages a superior process to follow.

Reviewing more recent work, Matthiesen (2011) discusses the role and support of creative thinking within the embodiment processes – the stage that he defines as that determining the material and geometrical considerations of the project. Through reflection on experience within the field, he notes the reflective nature of the process as a conversation between function and embodiment; describing the development of a solution as through the synthesis of information gathered in a prior analysis stage. This analysis may be direct and within the process as they work, or alternatively based on internal analysis of the experience of the designer as they piece together solutions from what they already know. As such, methods of support should encourage both the usual process of idea generation and synthesis of solutions, as well as the process of prior analysis. In essence this work suggests similar findings to that of design as a reflective process (Schon, 1983) and the importance of prior experience or expertise.

4.5.4 Creative Behaviour in Late-Stage Design

The study of later stage creativity has received even less attention. Eckert et al. (2012) describe the requirement for creative behaviour in later stage design, and the different form that it may need to take. As late stage design is different in many ways (see Section 3.4), including in higher constraint, complexity, and hence implication of design change, they claim that the requirement of late-stage creative behaviour may actually be problem solving while changing as little as possible about the design.

This is an interesting prospect in both application and implication for solutions. In practice, it suggests that a different type of exploration may be required for later-stages, with more analysis of the design situation and more development within strict constraints and guidelines. In terms of the output, it then also suggests that it may not be of high creative level in itself. Should the requirement of creative behaviour be minimal change, and hence change with lower inherent complexity, there may prove to be little by way of recognisable creative qualities in the solution. Creativity is then important within later stage design not because of the effect on output, but the effect on process. Creative behaviour need not dramatically change the result of the design, but instead increase the opportunity and feasibility for reaching a solution at all.

In terms of the appearance and result of creative behaviour in later-stage design, there are therefore multiple opportunities that demonstrate the worthwhile nature of research. As stated, creative behaviour may prove necessary when a solution cannot be reached by non-creative means. Here a link can be made to the TRIZ philosophy and methodology (Altshuller and Rodman, 1999), one part of which uses identification and analysis of contradictions in requirement or function (for example) to produce solutions to difficult problems. Due to its reliance on contradictions (such as a product must be both small for mobility and large for strength), TRIZ demonstrates particular applicability to the constrained situation of later-stage design.

In other cases of later-stage creative behaviour, its appearance may bear high similarity to its appearance in early-stage design, but with a variation in focus of working. One example is in the beverage can industry, where pressure performance is vital in order to safely transport and contain carbonated liquids. Conversely, because of the very high production rate of packaging, even a small increase in packaging thickness (which would increase performance) can cost a significant amount of money. In order to meet this discrepancy and produce a better output, significant exploration has occurred around the geometry of thin-walled pressure vessels and their application to the case of beverage packaging, leading to the complex, domed geometry found on the base of cans. This exploration occurred at a highly detailed level in the system hierarchy and focused largely on the analysis slight variation in small structural details, and hence can be considered creative behaviour in later-stage design. The interesting point surrounding this behaviour is that the creative process followed a pattern recognisable as creative by understanding in early-stage design, both in terms of the requirement for exploration and the production of an original, appropriate, and perhaps surprising result. Although potentially different to early-stage in several ways and working in a distinctly different situation, creative behaviour in later-stage design is therefore capable of producing both better results than would be achieved in a non-creative process, and of perhaps producing results where a non-creative process would not be successful.

4.5.5 Addressing the Knowledge Gap

There are no clear reasons for this knowledge gap to exist, or for research into later stage designer behaviour to not be a worthwhile subject. Perhaps, due to the constrained and closed nature of late-stage design, creative behaviour is not innately considered to occur and has largely been overlooked. Perhaps late-stage design is considered suitably well-defined to be solved in a more algorithmic way, as has been studied by some researchers over the years (see Chenouard et al., 2009, Scaravetti et al., 2006). Due to the potentially limited options of late-stage design in comparison to early, it may be thought that there will be less variation between designers and so less to learn. It may simply be that it has until now been overlooked.

Whatever the reason for the knowledge gap, there are benefits to be had from closing it. In reality, the constrained and closed nature of late-stage design is not a reason to discount creative behaviour. Each adds complexity, and with complexity comes difficulty in process for each late-stage designer. Whenever a problem arises that requires some creative thinking to overcome, the designer must solve it even though they are working within a difficult and constrained situation. Even beyond creative thinking for the sake of problem solving, any designer who is creative in late-stage design must be so in a way that is worthwhile of study. While it may seem that creative behaviour is less applicable to later stages due to the different design situation, in truth designers are still creative despite it.

The study of designer behaviour will in reality have similar benefits to the study of designer behaviour in general, or over early design stages. By gathering a detailed knowledge of what designers do it is possible to gain understanding of good and bad practice within design, knowledge which can be used in a number of fields.

From a management perspective, it may be possible to understand better processes and systems of later-stage design. For example, what behaviours lead to more or less efficient design, which lead to better results, and which lead to radical change. Different requirements will exist for each situation – in some cases a company may need results quickly with little scope for change, in another a company may need significant leaps in their product manufacturability, in yet another they may have large barriers to production that need wide-scale change to overcome. In each of these it may be better to follow different approaches to achieve the result, and through understanding of each it may be possible to make better decisions of which designers to work on which problems, when to implement different processes and stage activities, or what priorities to place within the design.

From an educational perspective, it may be possible to enhance training and teaching. Regardless of learning programme it takes time to become expert (Ericsson et al., 1993), and a great many approaches rely on experience. However, through understanding of those behaviours that reach better results or those that steer designers in different directions, it may be possible to inform students of better processes to use and the type of result that they can expect. Although there is certainly value in the process of learning through trial-and-error, teaching students of the likely consequence of different approaches could lead to better decision making.

From a support perspective, understanding of behavioural approaches may allow streamlining and enhancement of designer's individual processes. Although considerable care must be taken not to separate the benefits of experience from a designers working process, knowledge of the way in which a designer will likely behave in a given situation and for a given purpose can inform the development of tools and methods of support. These may vary in form dramatically, from computational methods of information gathering or analysis, to methods of ideation, suggestions of systems that complete certain functions in original ways, scheduling and process tools, or adjustments to current design tools. By gaining individual and specific knowledge of designers' late-stage behaviours, informed support can be created that is tolerant of their process, their style, their abilities, and their design situation.

At present, the knowledge to create such benefits does not exist. Within the study of the general process and early-stage design has provided understanding that can be applied and used, but without explicit consideration of late-stage design this cannot be assumed to be applicable in all cases. Late-stage design presents many differences to early, and must be understood specifically and in contrast to early-stage design and the process as a whole.

4.6 Summary: Designer Behaviour

Particularly in connection with the role of expertise, designer behaviour has been studied extensively within design research and in fields beyond. Through the behaviour that a designer displays they are capable of producing myriad different outcomes, and through the study of different types of behaviour ideas of better and worse practice can be formed.

Amongst those considerations most important for engineering design lie the notion of problem framing and problem structure, through which an expert will steer their process towards originality while maintaining quality (Section 4.2); flexibility in design process to allow a designer to take advantage of opportunities as they arrive (Section 4.3); the role of iteration and evolution of understanding as the design process continues, through the use of solution conjectures and evaluation (Section 4.3); and the different solution strategies that designers will employ.

These categories give a cross-section of the many different possibilities in design process. There are numerous influences and options acting upon each designer and within their process, and it is only through their study that eventual improvements and support can be made.

It is to this goal that the work now proceeds, through the formal research questions introduced in Chapter 1. Chapter 5 presents the research focus and questions in more detail, and provides the methodology through which they are addressed.

Chapter 5:

Research Focus and Methodology

To this point, the thesis has presented a review of the literature concerning the field of creativity, the engineering design process, and the role of individual designer behaviour within. It has also identified a significant knowledge gap – that study of designer behaviour within the design process has focused near entirely either on early-stage design or the process in general terms, with later stage design being neglected. Through the understanding gained from the field of creativity, the research project will begin to address this gap, with a primary research aim:

"TO CHARACTERISE THE CREATIVE BEHAVIOUR OF DESIGNERS WITHIN THE LATE-STAGE ENGINEERING DESIGN PROCESS"

To address this aim, it is necessary to form a methodological standpoint from which research will continue. Validity and reliability of process are important to increase confidence in results, and be sure that study produces robust findings that are representative of real life. This thinking permeates all levels of the research, from the way literature is studied and applied to the way studies are carried out and the way analysis is completed.

It is the purpose of this chapter to present these details of study, forming the fundamental research methodology that this project follows. In addition, this chapter formally presents the research questions that this work will address, and the objectives that will enable it to do so.

5.1 A Summary of the Research Focus

The literature review of this thesis has focused on three separate, but highly-relatable areas, the field of creativity, the process of engineering design, and the study of designer behaviour. Through these areas, and as presented in Section 4.5, a knowledge gap has been identified when considering the role of late-stage designer behaviour, particularly that of creative behaviour. Whatever the reason for this neglect, the body of work concerning other stages and the process as a whole demonstrate the potential usefulness that this study may produce.

It is to this end that this research project proceeds, and the research questions have been formed. These are detailed in Section 5.2.

5.2 The Research Questions

As introduced in Section 1.6 and implied through the literature review in Chapters two, three and four, there are three primary research questions to be addressed by this work

RQ1: What are the characteristics of creative behaviour in the engineering design process?

Primarily forming the research clarification element of this work, the study of creative behaviour is a highly complex subject. This is addressed initially through a comprehensive literature review, as presented in chapters two, three and four, studying current understanding of the field of creativity, the context of engineering design, and the behaviour of designers within. Through this combination of fields, the literature review informs of current limits of understanding in the area of creative behaviour, as well as provides a structure for study based on existing theory. It is also through this literature review that the primary knowledge gap, research aim, questions, and objectives are determined.

By studying not only products, but also the characteristics of behaviour manifest in both the designer and the process by which they develop a product, the study of behaviour allows understanding of both outcome and those causal mechanisms by which it comes to be. As the definition of a creative product inherently implies superior appropriateness to a non-creative alternative, the context of creativity research provides a perspective that should inherently focus on behaviour that leads to superior solutions, and hence provide understanding of potentially better practice.

From the state-of-the-art understanding of creative behaviour, following the research aim and objectives identified during the research clarification methodological stage, further research can develop and refine theory applicable to the particular area of interest. This process is addressed by Research Question Two.

RQ2: How does creative behaviour manifest within the late-stage design process?

Due partly to its breadth in applicability and partly to the contrasting views and lack of consensus in its meaning, this relatively young field has to date had little focus on the later-stages of engineering design; different in structure and design situation, but equally valid as a part of the overall design process. This represents a critical lack in knowledge, and one that has potential to provide significant benefit in a variety of areas, including process enhancement, designer support, management strategy, and design education.

As this question focuses directly on a gap in current knowledge, it requires original research to address. Although in part informed by literature, this occurs through a combination of descriptive and prescriptive study. By observation through empirical research, this approach takes existing theory on creative behaviour, and confirms, refines or rejects based on the particular context of later-stage design.

As with all original research, there is also within this question the need for demonstration of validity of findings, both in terms of methodology and in applicability to and representation of real-life design. This aspect is addressed through choice of methodology and assessment of validity within the results, and also through the process of addressing research question three.

RQ3: What are the opportunities for designer support in later-stage engineering design?

In a practical sense it is important for research to be applicable to reality, and useful beyond the purely academic. Within the field of engineering design research, it is through the application to industry that the usefulness of research is realised, and so it is through consideration of the potential effects and benefits of new understanding that research can be justified. Within this work this requires two separate strands of thought, completed through similar method but with very different focus.

Foremost of these is the forming of implications for industry. As completed by a combination of literature review and original research, characterisation of later-stage behaviour provides understanding of actual occurrences in the process of designers. The further task to this is to then understanding the implications that these occurrences create, and hence to infer opportunities from results. From the general characterisation of designer behaviour, there is scope for these potential opportunities to concern a number of areas including designer support, training and education, and process management. The particular goal of this research is in the support of designers, through suggestion of directions for tools, or stimulation of certain behaviours leading to improved output or process. Such support and the understanding needed to develop it would then feed into the development of engineering education, process management, and design.

Second is the importance of validity of findings, both in terms of the research itself and in terms of industry context. Due to the many complexities of design and creativity, it is important that any study considers the variation that occurs between the settings of academia and industry. Further, to maintain applicability in the industrial world, understanding must be gained of the implications of opportunities in a real-life setting, and how they may vary dependent on circumstance, project, company and designer. Again, such analysis can be conducted through a combination of literature review and original research, through observation of industrial designers and study of the specific variables to which they are subject.

5.2.1 Assumptions of Research

Based on the literature analysed, there are some assumptions that are made within this work.

First, creative behaviour is not synonymous to creative process, and can be observed directly. The latter by definition requires the production of a creative product, the former implies only that the designer demonstrated some behaviour that made a creative product a possibility. It is therefore a necessity for a creative process to contain creative behaviour, but not for creative behaviour to result in a creative process. This distinction recognises both that creative and non-creative products may be produced by similar processes, and adds a deeper layer of understanding to analysis.

This work defines a creative product as "better" than its alternatives, but recognises that other considerations to what is best for each situation must be made. This definition of creative product is, quite logically, very product-orientated. It is therefore entirely possible that in some design situations a creative product may be better than alternative designs, but still detrimental to the process as a whole. For example, in cases limited time or budget, the creative process may prove unfeasible; and in cases of small change and iterative design a company may see creative behaviour as unnecessary. Such judgements are to be made on a case-by-case basis. However, should it be of preference, the study of creative behaviour is equally capable of creating the knowledge to steer designers away, as it is towards.

Finally, in terms of the actual appearance of creative behaviour, there is no reason to expect later stage to differ from early stage. In both cases a designer must explore in order to diverge and converge, it is only through exploration that originality can be reached. The expected differences are not then in the act of exploration itself, but in the focus of exploration, the conditions under which that exploration occurs, and the way it is completed. For example, at a later stage of design, creative behaviour may not be the discovery of radical change or new functional structures, but rather the exploration of how to solve a problem while changing as little of the design as possible (Eckert et al., 2012).

5.3 Generalised Research Methodology

While the field of design research is rapidly growing, there is a lack of consistency and clarity in methodological approach undertaken by researchers (Blessing and Chakrabarti, 2009). This results is a lack of scientific rigour in results, and hence a lack of repeatability, validity and applicability of findings.

To improve rigour it is necessary to adopt a research methodology, the framework by which the research project itself is carried out. Within this work, the well-accepted Design Research Methodology (DRM) of Blessing and Chakrabarti (2009) is used, partly due to its wide use within the field of design research; partly due to its easy adaption to the project specifically; stepping from developing theoretical understanding, to observation of phenomena, to specific and focused study of the main study variables, to subsequent evaluation and validation within wider context (see Figure 17).

5.3.1 The Role of Theory

Dependent on the availability of existing theory, research methodology can take one of two approaches. *Deduction* takes the assumption that existing theory describing the phenomena of interest is available, which it then confirms, rejects or revises through a process of study. *Induction* takes the converse stance, that existing theory is not available as a starting point, and uses methods of study to produce theory as an outcome. Within this work, the lack of theory relating to the creative behaviour of designers in later-stage design necessitates inductive study to produce theory. Due to the breadth of related literature however, as presented in Chapters 2, 3, and 4, there is a significant body of theory upon which initial assumptions and structures for study can be formed. In this sense, the availability of existing theory facilitates the formation of the research approach used throughout the thesis, and the formation of the framework and coding scheme used for analysis as presented in Chapter 6.

Taking a realist view, the design process can be considered a transformation from action of a designer to outcome, completed through a number of mechanisms (see Robson, 2002) (see Figure 16). This view understands that an outcome occurs and is dependent upon a potential number of mechanisms, which can be understood and tested through theory, observation, and experimentation. In the context of this thesis, there is then a collection of mechanisms in a designer's behaviour by which a creative outcome is produced, that can be understood through understanding of theory and observation of behaviour.

The study of engineering design and designer behaviour then inform this model, describing the typical actions completed by designers, the mechanisms by which they design, the outcomes produced, and the context of their working. This model creates a basis of understanding for research; in comparison with theory describing the early-stages of design or the design process as a whole, a deductive approach can investigate each element of the model through observation of the actions, mechanisms, outcomes and context of later-stage design. Thus this process will utilise existing theory directly, used as a basis for study, and confirmed, rejected or revised as dictated by findings.

The field of creativity further informs this process. Taking the possession of creative qualities in an outcome as improvement by definition (see Section 2.2), the study of the actions, mechanisms and context under which a creative design process occurs, in direct contrast to a non-creative process, will yield theoretical understanding of creative practice, its use, and its suitability. In this way, the field of creativity provides a structure and background of understanding, chosen to allow direct study of action, mechanisms and context that lead to improved outcome.

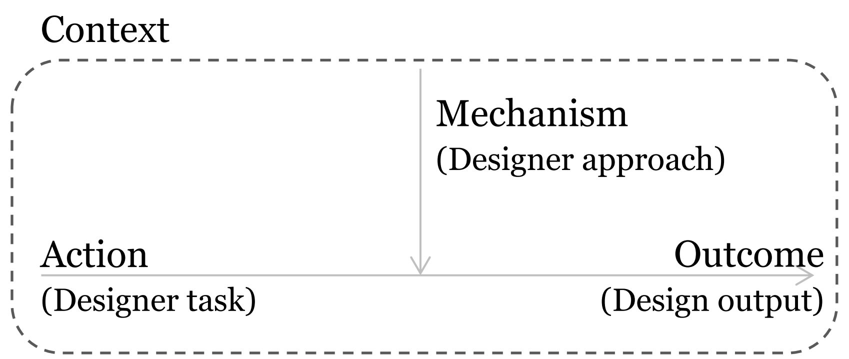


Figure 16: The realist model of causation (Robson, 2002)

A particular strength of the use of this model is one that ties closely to thinking on the four pillars of creativity (Rhodes, 1961) as described in Section 2.1. By explicitly considering all four system aspects, deeper understanding of the process of design and the causal relationships within can be determined (Briggs, 2006). Similarly, through the explicit study of the creative person as they complete a creative process, with the creative product considered a separate but related entity, causal relationships can also be determined. As such, this study allows understanding not just of creative outcome and the process by which it comes to be, but rather the relationships between a person and their actions, the mechanisms of their process, the context of their work, and the eventual effect on the outcome.

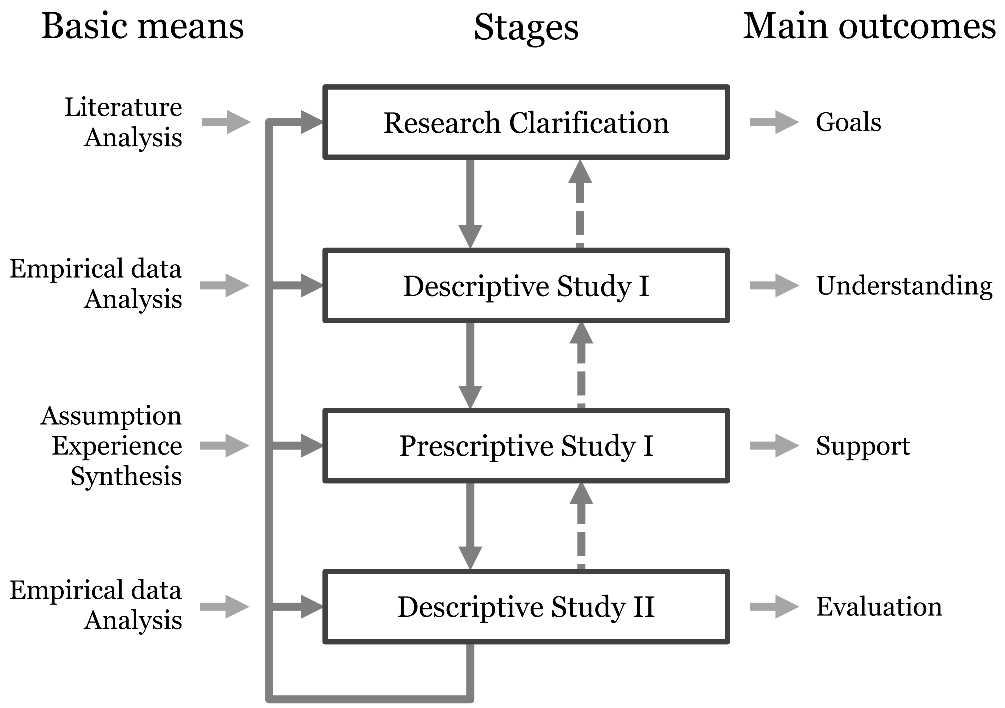


Figure 17: The DRM process (Blessing and Chakrabarti, 2009)

5.3.2 The Process of Design Research Methodology

Formally, DRM proposes a research process as occurring through a combination of research clarification, descriptive study, and prescriptive study (Blessing and Chakrabarti, 2009). These elements are, dependent on the research subject and purpose of study, completed to varying degrees of detail. For example, in its most commonly taken form, the DRM process is designed for the purpose of the identification, introduction, and validation of design tools, methods, of support into the design process. As part of this research process, DRM states that it is necessary to complete a process of research clarification and initial descriptive study to fully understand the problem, a prescriptive study to introduce the method or tool under development, and a final descriptive study to validate the tool in use. These four stages are summarised below.

Research Clarification

The purpose of research clarification is to provide understanding, problem scope and structure, from which the further studies can proceed. This includes determining research goals and objectives, as well as identifying research problems, and areas of focus for study.

Descriptive Study One (DS-I)

The purpose of the initial descriptive study is to provide a better understanding of the phenomena of interest, through empirical research and observation. This both clarifies the primary factors influencing the design situation, and those uncovered through research clarification, as well as providing direction and focus for the prescriptive study.

Prescriptive Study

The purpose of the prescriptive study is to build upon the observations made within DS-I, producing deeper understanding of the phenomena of interest and informing the revision and development of appropriate theory. Informed both by the research clarification process and DS-I, and completed in part concurrently with DS-II, this study utilises an informed, controlled setting to allow the generation of more specific findings.

Descriptive Study Two (DS-II)

This study acts as evaluation of the process and findings of the PS, as well as DS-I, to ensure validity and reliability in findings and conclusions from research. This provides confidence in revised theory, initially taken from existing literature, and developed through the results of DS-I and PS.

5.3.3 DRM within this Work

Due to its aim, this work takes a non-standard form of DRM. As it aims to produce characterisations of later-stage creative designer behaviour, identified within the knowledge gap as being subject to little research, there is no goal to introduce methods, tools, or support as part of the work. As a result, the entirety of the work presented within this thesis is categorised as belonging to Research Clarification and Descriptive Study One. This is a fully justifiable approach to take (Blessing and Chakrabarti, 2009); when little understanding exists on a subject, a comprehensive and detailed study of the subject is required in order to provide the grounding upon which further work, including the development of methods, tools, support, can occur.

These research questions are therefore addressed through the research clarification and DS-I stages of the DRM methodology (Blessing and Chakrabarti, 2009). This section provides general detail of the methods used in each stage, and their contribution to the research questions.

Research Clarification

As presented in Chapters two, three and four, research clarification has occurred through literature review, focusing on the fields of creativity, engineering design and designer behaviour. Accordingly this methodological stage concerns in large RQ1, identifying the current state-of-the-art understanding of creative behaviour within the context of engineering design. Additionally, as it is from the research clarification that the formal research aim, questions and objectives are formed, this stage informs each study and its interpretation. As a result, the research clarification in no small part provides the understanding that frames the findings of each other stage.

DS-I: Study One – The Logbook Study

Forming the majority of research completed within this work, the DS-I stage occurred through several steps.

The first of these involved the development, through existing theory and the design record of a single designer's working over a longer-term project (22 weeks), of a coding scheme and framework for analysis of creative behaviour in later-stage design was formed.

Following, and acting both for validation and formation of findings, the coding framework was applied to the working of seven designers (separate to the one used for development) working on a term identical in process but different in subject matter. This study forms Study One, and is referred to as the Logbook Study.

Through this indirect observational process, a detailed understanding of the method of analysis for later-stage creative behaviour was formed. In addition, some preliminary and some tentative findings could be made and used to inform the direction of the prescriptive and second descriptive studies. This process therefore allowed understanding of the behaviour of designers in connection to the theory studied as part of the research clarification stage, and allowed the identification of discrete observation to be completed subsequently.

This study methodology is detailed in Chapter 7, with results presented primarily in Chapters 8 and 9.

DS-I: Study Two – The Observation Study

Informed by both the research clarification and study one, this study involved a combination of both undergraduate and expert designers working within familiar surroundings (e.g. students working in a university; experts working within their typical industry surroundings). Its purpose was to allow more detailed study of designer behaviour in a controlled environment and according to a controlled task, thereby augmenting the findings of study one (as elaborated in Section 7.5) and developing further results in itself. This study forms Study Two, and is referred to as the Observation Study.

Through four discrete stages, the study replicated in its procedure a standard design process from early stage to late stage, and was designed to encourage focused working practices within each. This study allowed detailed analysis of 18 designers working within later-stage design, and the creative behaviour that each displayed.

In addition, each design output produced within study two was assessed for quality according to a metric-based approach, and a consensual assessment technique. This process was completed for the sake of increased understanding of the implications of design behaviour and creative behaviour.

These study is detailed in Chapter 7, with results presented primarily in Chapters 8 and 9.

DS-I: Study Three – The Contextual Studies

Acting for the purpose of evaluation and validation, this part of the descriptive study consisted of several complimentary steps. Firstly, a detailed comparison of working practices between the expert and less-experienced participants in each study. Secondly, a longitudinal observation of industry designers working on industry projects in typical surroundings. These studies are collectively referred to as Study Three, or the Contextual Studies.

These studies collectively describe the differences between expert and less-experienced designers, and hence inform analysis of the implications of the findings of studies one and two. Further, the direct observation of industry designers working on industry projects allows confirmation where appropriate of findings made within laboratory studies, carefully considered in tandem with the context in which the industry designers were working, and the influence that this context produces.

A combinatory approach such as this provides evidence for the validity of findings in each other stage of the research process, as well as informing understanding of the variation produced by the industry situation and expertise in design.

The further methodology of this work is presented in Chapter 10, alongside its results.

5.3.4 Research Objectives

In support of the research questions, four discrete research objectives have been developed. Chosen to provide direction in study and to inform the addressing of each research question, they are presented below.

1. To identify the typical features of creative behaviour within design.

Method: Literature review (primary) and empirical study.
Outcome: Characterisation of creative behaviour within design.
Addresses Research Question One.

2. To identify the typical features of the later-stage design process

Method: Literature review (primary).
Outcome: Characterisation of the later-stage engineering design process, purpose and influencers.
Addresses Research Question Two.

3. To investigate the appearance and integration of creative behaviour within the late-stage design process.

Method: Empirical study, involving longitudinal observation and laboratory study.
Outcome: Characterisation of creative behaviour within later-stage design.
Addresses Research Questions One and Two.

4. To develop understanding of the opportunities for improvement of creative behaviour within the late-stage design process.

Method: Empirical study, involving longitudinal observation and laboratory study.
Outcome: Understanding of industry validity of findings, and opportunities for design process and outcome enhancement.
Addresses Research Question Three.

5.3.5 Research Output

As stated by the research aim and questions, the output of this work is in understanding and characterisation rather than support and process methods. Due to the many influences on designer behaviour and the many forms that it may take, a detailed, descriptive understanding of actual behaviour is required before any implication and application can be explored. Relating back to Figure 12 in Section 3.5, this work forms a descriptive analysis of designer behaviour, which can provide grounding on which prescriptive development can be made. In order to intervene, one must first understand; in order to understand, one must first observe.

5.4 Summary: Research Methodological Structure

This chapter has presented the methodology by which the research project as a whole is completed. Table 13 presents the stages of methodology, in context of the chapters of the thesis.

Following the structure provided by DRM (Blessing and Chakrabarti, 2009), this work completes a process of research clarification, followed by a highly comprehensive descriptive study. This produces detailed understanding of the phenomena of interest, and the basis upon which much further work can be completed.

Utilising existing theory to allow understanding, and some inductive reasoning in the formation of the coding scheme presented in Chapter 6, several empirical studies are completed, used both for the purpose of confirmation of existing understanding and for the purpose of theory development.

Based on the approach of critical realism, this work takes the view that the outcome of a designer's process is a consequence of the actions that they complete, the mechanisms at work within the process, and the context of its occurrence. Therefore, through the study of designer process from the perspective of creativity research it is possible to analyse actions and mechanisms that are more likely to lead to creative outcomes, within the specific context of later-stage engineering design.

Repeating comments made in Section 1.7, this thesis follows a structure chosen to maintain consistency of subject between chapters. The initial section concerns literature and background, the formalisation of the research project and the research methodology. The second section concerns the attainment and presentation of results towards the primary aim of the work – characterisation of designer behaviour within later-stage design processes. For this reason, Chapters 6 and 7 contain the development of the framework for research and methodologies of the logbook and observation studies. The following two chapters are then able to present results from these studies, grouped by theme for consistency in understanding. The third section then provides methodology for the contextual studies and consequent results. This structure allows findings to be presented according to consistent theme, rather than study in which they are manifest, and hence prevents repetition. Cumulative discussion of all findings can then occur in the fourth section.

Table 13: The structure of the thesis

Chapter	Description	Methodological Stage	Research questions	Research objectives
Section 1: Research Clarification Stage				
Chapter 2	Through literature review, detailed analysis of the state-of-the-art of the field of creativity.	Research Clarification	1	1
Chapter 3	Through literature review, detailed analysis of the process of engineering design.	Research Clarification	2	2
Chapter 4	Through literature review, detailed analysis of the traits of designer behaviour.	Research Clarification	1	1, 2
Chapter 5	Presentation of the research methodology, aims, questions and objectives.	--	--	--
Section 2: Presentation of Primary Findings				
Chapter 6	Development of the coding scheme and framework of analysis.	DS-I	--	--
Chapter 7	Presentation of the methodologies of studies one and two.	DS-I	--	--
Chapter 8	Presentation of results concerning creative behaviour and creative approach displayed by designers in studies one and two.	DS-I	1	1, 3
Chapter 9	Presentation of results concerning behaviour, comparison of behaviour between stages. Results taken from studies one and two.	DS-I	2	2, 3
Section 3: Presentation of Contextual Findings				
Chapter 10	Presentation of the methodology of study three. Presentation of results concerning the evaluation of results, and validity in context of industry and expert designers. Results taken from studies one, two and three.	DS-I	3	3, 4
Section 4: Discussion and Conclusion				
Chapter 11	Discussion of the findings from the research.	DS-I	1, 2, 3	1, 2, 3, 4
Chapter 12	Concluding statements	--		

Chapter 6:
The Framework for Research

The Chapter marks the beginning of Section Two as shown in the tables of thesis structure. The purpose of this section is to present the framework and coding scheme used as the primary source of analysis of designer behaviour within later-stage design.

The specific purpose of this chapter is to present the manner in which designer behaviour is studied, and patterns within it are identified. This is completed through the individual tasks completed by designers within their process, which are in turn identified through individual *entities* that form the input and output of each. Eight different types of task that a designer may complete are derived from literature and formally presented. These fall into three independent categories; whether a task is creative or non-creative, the type of output that a task generates, and the type of transformation that a task involves. General behavioural approaches are determined by majorities of certain task types appearing in the process of the designers studied. A detailed explanation of these thoughts form the majority of this chapter.

Behaviour itself is studied through two observational studies. Study one involved a 22-week indirect observation of seven non-expert participants, studied through their logbooks. Study two involved a four hour laboratory study of 18 participants; twelve non-expert, two non-expert but industrially based, and four expert in industry. It was conducted through direct observation through written records, recorded video and screen capture.

Additionally, the quality of solutions of study two was assessed through the use of two separate methods. The first of these involved a metric-based method derived from the project specification, the second involved an expert-judged method based on the opinions of highly experienced engineers.

This chapter forms an introduction to the results chapters, eight and nine.

6.1 The Framework for Research

In order to complete the research aim, it is necessary to establish a framework for analysis that is particularly suited to the project. To do this it must complete a number of criteria, identified through the literature review.

1. **There must be a primary focus on analysis of behaviour and process, rather than on product or output.** Throughout this thesis there is a focus not on identifying output and then tracking back to characterise the process, but instead on studying the process directly. This allows better understanding of the variations in process that can occur, and the potential causal relationships between a designers' behaviour, the design process and the eventual output.
2. **The framework must allow identification of creative behaviour within a designer's process, in contrast to non-creative behaviour.** Again, this must have a process-based focus rather than an output based focus. This work holds that it is through a process that the output comes to exist, and that the creative behaviour of a designer will allow the production of a creative output. It is therefore through direct study of creative behaviour that a better understanding of the mechanisms by which a creative output come to be can be found.
3. **The framework must be applicable across the context of engineering design.** A particular advantage of study through the behaviour of individual designers is relevance across design situations. In industry, there are a multitude of different processes, products and priorities. By classifying by the individual and their behaviour, who are a constant presence across industry, the framework can ensure wide applicability.
4. **The framework must be applicable in all stages of the design process, but particularly within the later-stages of design**. As the framework studies behaviour and process of designers, several of those characteristics of later-stage design within Table 10 are influencers, rather than data points. However, the consideration of a changing focus in activity as the designer progresses from early stage design to late, demonstrates the breadth that the framework must cover.
5. **The framework must be exhaustive in application.** It is particularly important when studying behaviour that all actions are analysed, so as not to miss vital influences and circumstances. For this reason, the framework must be applicable not only to all activities within the process, but also to all behaviours that a designer may employ within.
6. **The framework must be applicable to a variety of data types.** The process of designer observation, as performed in this research, can be through a number of means. As such, the framework must be applicable to the media that designers use within their process, as well as video data and spoken word.
7. **Creative behaviour must be inherently linked, but fundamentally independent from tasks.** A primary assertion of this work is that designers will demonstrate creative or non-creative behaviour through their process, and that the appearance of this behaviour is dependent on the individual. It must therefore be possible for each type of task to be completed in either a creative or non-creative manner; requiring tasks and creative behaviour to be identified according to separate methods.

It is only through completion of all of these criteria that the framework can be expected to be effective in purpose, and robust in results.

6.2 The Method of Analysis

The primary purpose of this research is descriptive, empirically observing designers in order to produce the understanding that can be used for prescriptive intervention in future work. To complete this aim, a method of analysis is needed that is applicable to analysis of actual behaviours of designers, based appropriately on past literature. For this reason, the research uses the framework to allow a content analysis process.

Content analysis is a well-accepted analysis method in a wide array of fields, particularly the social sciences (Krippendorff, 1981, Elo and Kyngäs, 2008, Potter and Levine Donnerstein, 1999). As the name implies, it uses direct observation of the occurrences of actions, words or thoughts of participants, placing each occurrence into a category suitable for analysis. This process occurs according to a set of guidelines, termed a coding scheme, which is developed according to each framework and for each data type.

Content analysis schemes can be formed either deductively from literature or inductively from the data, with varying consequences for validity (Potter and Levine Donnerstein, 1999, Elo and Kyngäs, 2008). A deductive process ensures validity in the scope of the wider research field, relevant and informed against existing theory and results. The inductive process ensures that analysis is highly applicable to the particular set of results, is exhaustive in analysis method and is suitable to the data type. In the former case results show face validity, the statement that results will demonstrate what they are meant to demonstrate as according to understanding within literature; in the latter the results show internal validity, the statement that the results from the data reflect evidence within the data itself, and are not the result of unrepresentative data or an inability to study the phenomena of interest in each specific case (Robson, 2002).

However, one type of validity does not guarantee the other. A deductive process will be valid in a broad scope, but the fact that the analysis method has stemmed from sources other than the specific experiment and its context means that categorisation may be difficult. When categories come from another source, there is no certainty that all will be applicable to the specific set of data, or that the specific data will not require additional categories to be introduced. Conversely, an inductive process will produce categories that are highly suited to the individual experiment, but the relationship to the wider research field is very unclear; not necessarily unrelated, but further study of validity in wider context is needed.

To account for these issues this research used a primarily deductive process, using existing literature to inform the development of the framework and coding scheme, while still maintaining awareness of the observations that would occur through reference to actual data. Using an actual design record of a 22-week project (in the form of the authors logbook), inductive understanding was developed of the manner in which data fit into categories of existing literature. These categories could then be developed with careful consideration of both the data and their theoretical underpinning. The fact that it was the authors logbook used for reference was particularly useful, due to the ability to recall past behaviour given definitive prompts to memory (Gero and Tang, 2001). Due to potential inaccuracy in the details of tasks and to avoid bias, this design record was used only for scheme development, and not for any reported analysis.

As they are highly inter-related, the following sections describe the framework and subsequent coding scheme concurrently and in detail, with the literature on which they are based. After description of the framework and coding scheme, Chapter 7 continues through description of two studies to which they were applied.

6.3 Identifying Tasks within Designers' Processes

As described by activity theory, this work defines behaviour through the sequence of tasks that designers complete. This leads to the formal definition (see Section 3.2):

Behaviour The mental and physical tasks completed by a designer over time, through which individual activities are completed.

In order to identify and study behaviour from the viewpoint taken within this work, it is then necessary to identify designers' individual tasks, separate to the identification of activities or the assessment of products. Key to behaviour in this definition is sequence; one task indicates only an action, and it is through multiple actions that patterns can be found. This need creates further requirements that the process of identifying tasks must complete (Table 14). It is only through completion of all of these requirements that the eventual coding scheme will be useful.

Adding to the definition of behaviour, *approach* is defined as the manner in which behaviour is completed, and is distinguished through the appearance of different tasks (either individually or in pattern) within similar activities. This definition requires the coding scheme to operate at quite an abstract level; to allow for differing approaches tasks must not be identified through the activities upon which the designers are working (i.e. "dimensioning tasks", ties the task too closely to the dimensioning activity).

Table 14: Requirements for the coding scheme

	Requirement	Comment
1	Tasks must have definitive input and output	To record sequence, it must be clear when one task ends, and the next begins.
2	Tasks must be discrete in purpose and focus	For the sake of analysis, it must be possible to individually state the purpose and focus of each task in wider context.
3	Tasks must be exhaustive in classification	All occurrences made by the designer in relation to the project or process must be classifiable by the framework.
4	Tasks must be quantifiable	The purpose of this form of content analysis is to provide categorisation of actions, which can then be analysed numerically. The framework must conform to this need.
5	The coding scheme must be applicable to the work of individuals	Identification of tasks must not be reliant on the study of multiple designers simultaneously.
6	Tasks must be independent of process activities	Stating that designers can complete differing tasks in identical activities, tasks must not be pre-defined in an activity context.
7	The coding scheme must be applicable across different engineering processes	To allow comparison of designers, the coding scheme must be applicable regardless of the process and product upon which they are working.
8	The coding scheme must be applicable across design stages	To allow understanding of the later stages of design in context, the coding scheme must also be applicable to early stages.

6.3.1 Categories of Tasks

Following the content analysis procedure, tasks will be categorised according to their type. It follows that the framework must describe all different types of task that can be completed by a designer. Creative theory as described in Section 2.4 allows a method to be brought to this need. The use of creative theory here plays both the role of ensuring relevance to existing literature, and directly designing the coding scheme from the perspective of creative behaviour.

Paraphrasing from the work of Gero (1996) and Dym (1994), creative design can be described in two different ways:

Table 15: Two forms of creative design

Gero	Dym	Description
Creative	Class 1 (creative)	Creative through the exploration of, and use of new knowledge and variables introduced for the design.
Innovative	Class 2 (variant)	Creative through how known variables and knowledge sources are used within the design.

These two forms of creative design give a strong distinction between two different behaviours of designers. They can either be creative in their finding of variables and knowledge for the design, or they can be creative in how they manipulate known variables and knowledge. Therefore, the tasks that they complete either concern the *variables and knowledge present for use* within the design process (i.e. new variables or existing variables), or they concern *the way in which knowledge and variables are used* (i.e. the manner of use of variables regardless of their status as new or old). The former applies to the production of the resources that a designer can use, and the latter applies to the production of the actual design itself.

It is this distinction that forms the basis for distinction between types of tasks. As will become clear throughout this chapter, all tasks of a designer can be described through these means, defined as in Table 16.

Table 16: The two fundamental task types

Task Type	Definition
Information	Any task concerned with the development of knowledge or introduction of variables into the design. Thereby concerned with the knowledge content that is present for the design process.
Application	Any task concerned with the actual design output and the use of knowledge or variables within it. Thereby concerned with how the present knowledge is used in the design itself.

*The terms *information* and *application* are introduced as their meaning is relevant to the focus of the type of task, but have not been directly extracted from literature, and are not intended to be synonymous with other literature terminology.

These two task types are taken from the ways in which a designer can be creative, according to literature. However, as stated in the requirements of the framework, the coding scheme must be able to classify both creative and non-creative tasks. For this reason the definitions in Table 16 do not make any distinction according to creative behaviour; each is intended to be applicable regardless of the appearance of creativity. As example, when creative, an information-type task will explore the possible knowledge and variables that can be used in a design; when non-creative, an information-type task will not introduce new knowledge or variables, but will be concerned with the development of those already known. When creative, an application-type task will explore how all knowledge and variables could be applied to form the actual design solution; when non-creative, an application-type task will develop the actual design solution, using knowledge and variables in expected and understood ways. More tangible examples of each are given in Table 17.

Table 17: Examples of information- and application-type tasks

Task type	Creative / Non-creative	Example
Information	Creative	Search for different materials that fit the specifications for a particular component.
Information	Non-creative	Clarify the typical material properties of low-carbon steel.
Application	Creative	Produce several potential configurations for a single sub-system.
Application	Non-creative	Dimension a component according to inter-part relationships and constraints.

Information-type and application-type tasks can therefore be used to describe both creative and non-creative tasks. They are also an exhaustive distinction – no tasks have been found that cannot be classed as of a form that concerns the resources available for design (therefore variables and knowledge, information-type), or that concerns how those variables and knowledge are used for the actual design (application-type).

The descriptions of information-type and application-type tasks can be better understood through consideration of tasks in a process sense. For example, an information-type task may identify a new resource that can be used in a design, such as a new technology. An application output task may then explore how that resource would be used within the physical design itself. A further information output task may then analyse the use of that resource in the actual design for the purpose of re-formulation of the problem. A final application output task may then finalise the configuration and dimensions of the design for production. In each case, information-type tasks are concerned with the development of the knowledge that can be used in the design process; and application-type tasks are concerned with how the knowledge and variables are used within the actual design.

This classification by information-type and application-type has parallels in existing literature on knowledge-based theories of design, such as that between the set of domain knowledge (similar to *information-type*) against the design description used (similar to *application-type*) (see Klein, 2000, Stokes, 2001).

An implication of this method is that tasks are identified by output – by the purpose that they have of either developing knowledge or variables as an output (*information-type*), or of using knowledge or variables in the design, where the design itself forms the output (*application-type*). This is an important consideration to make, partly as it leads on to the method of identifying individual tasks (as will be explained in a following section), and partly as it also implies that tasks could also be classified in methods other than just output. An alternative method of identifying types of tasks that uses the same categories, but does not classify by output is presented in Section 6.3.4.

6.3.2 Individual Tasks

In order to identify individual tasks as belonging to these categories, this framework borrows from the Methodology for Knowledge Based Engineering Applications (MOKA) (Klein, 2000, Stokes, 2001), a standardised method of storing and representing knowledge used within the engineering sector.

MOKA describes all tasks as composed of individual "entities", in which an entity is an individual physically real or conceptual "product object" of the design. A task (termed *activity* in MOKA) forms a transformation between entities, therefore requiring entities to form the input and output of any task. A task can therefore be defined formally:

Task A transformation of one or more input entities into one or more output entities, completed by a designer.

There are three different types of entity described by MOKA. To these three this work adds an additional entity to specifically classify knowledge used within a design, as this form of discrete object is not explicitly accounted for in MOKA. Definitions of entity types are given in Table 18. Significant similarities to these entities can be found in well-accepted literature. The Function-Behaviour-Structure (FBS) scheme of Gero (1990) also uses each entity type, describing the design process through individual transformations and comparisons between one type and another.

Table 18: The four task entities

Entity Type	Definition
Knowledge (K)	What is known about the output and what describes it, in terms of background, domain and context.
Function (F)	The purpose of the output, what the product or system must do.
Behaviour (B)	The way that the output completes its function.
Structure (S)	The discrete objects that create the output, either physically or virtually.

Table 19 provides more tangible examples how each type of entity may manifest in a designer's process, and Figure 18 provides real-data examples of entities within a logbook.

Table 19: Examples of task entities

Entity Type	Example
Knowledge (K)	A discrete statement of fact regarding an available resource, such as a material property.
Function (F)	A statement of requirement for the output, such as the performance attributes listed in the output specification.
Behaviour (B)	A layout or configuration of the working structure of the system.
Structure (S)	The specific dimensions of an individual component.

K

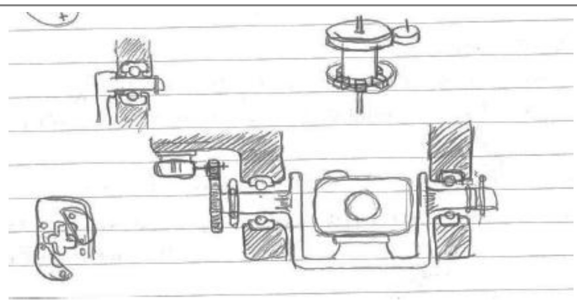
Product	Maximum Altitude (m)	Price (£)	Mass to Transport (KG)	Volume to Transport (m3)
Draganfly X4	2400	5400	9	0.085
Astrovision	150	35.7	0.2	0.018
EasyUP AP1500	15	1400	24	0.068
General Kite	100	100	3	0.085
Kingfisher	70	5745	6	4.5
Draganfly X8	2400	20500	28.8	0.1
Honeywell RC	3000	12000	9	4.5

F

To provide an effective & competitive solution the design must embody the following features:

- Target price ≈ £500 to remain affordable to every day users, yet complex enough to be a valued tool.
- High portability → < 20kg for a single person to carry
  ↳ fit within a standard 35L Hiking back pack.

B



S

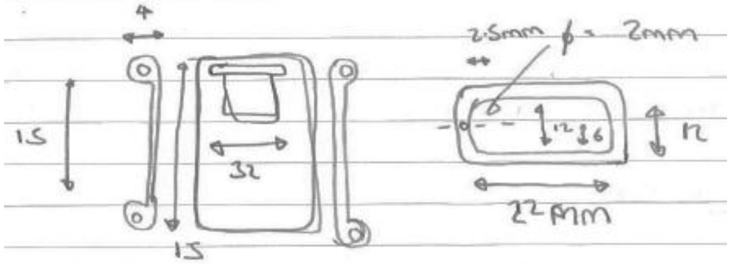


Figure 18: Real data examples of entities within data, from the logbook of study participant 1B

Within Figure 18, the *knowledge* entity is identified as a statement of information regarding a number of potential competitor products. The *function* entity is identified as a statement of requirement for the final product and its function. The *behaviour* entity is identified as a layout configuration for the camera. The *structure* entity is identified as a dimensioned drawing of a component.

6.3.3 Assigning Entities to Task Types

In Section 6.3.1 it is argued that designers complete information- or application-type tasks. This section describes tasks as transformation of entities. These two statements must be integrated, aligning the possible entities with individual types of task. Looking at the definitions of each entity, both knowledge and function entities consider the knowledge and variables that are present in the design, hence relating to *information* type tasks; while behaviour and structure entities consider how knowledge and variables are applied to the design, hence relating to *application* type tasks. The use of entities can therefore also be used to identify the type of task being completed. The appearance of a *Knowledge* entity output (such as when the designer is developing or exploring design information), or a *Function* entity output (such as an exploration of functional structure) indicate that they are completing *information-type* tasks. The appearance of a *Behaviour* entity output (such as a system layout), or a *Structure* entity output (such as a material selection for an individual component) indicate that they are completing *application-type* tasks.

Table 20: Entity types in relation to coding scheme classification

Entity Type	Entity Classification	Task type, when appearing as output
Knowledge (K)	Information	Information-type
Function (F)	Information	Information-type
Behaviour (B)	Application	Application-type
Structure (S)	Application	Application-type

It is in this identification method that this work differs from the use of entities within the FBS scheme – tasks can be identified explicitly according to their output as belonging to one particular category of type of entity.

Entities can then be considered as in Figure 19. They can be of four separate types, two of which indicate information-type and two of which indicate application-type. In this thesis, no analysis occurs through the distinction between entities of the same classification (i.e. information-type or application-type), but of different entity types (i.e. knowledge-type and function-type). Only the fact that entities are of information-type or of application-type is taken into account.

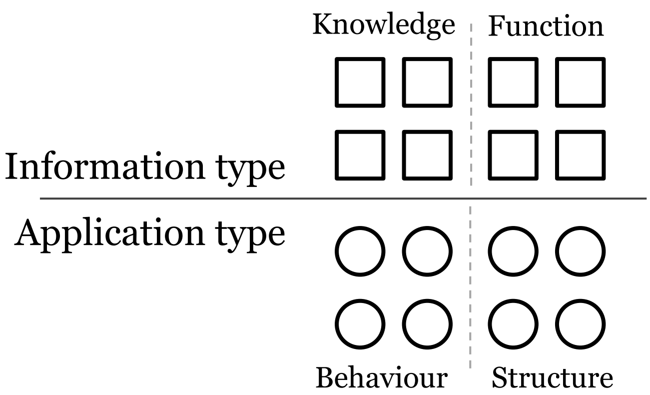


Figure 19: Information and application type entities

As a task is a transformation between a discrete input and a discrete output, a task must occur as a transformation of one (or a group) of entities into another (or another group), as shown within Figure 20. Part (1) shows a task in which both the input and output entities are of the same type (application-type by the labelling within Figure 19). An example of this could be the final dimensioning of a component, in which the input entity forms the initial representation and the output entity is the fully-dimensioned component. Part (2) shows a task in which the input and output are of different types (application-type to information-type). An example of this could be the stress analysis of a system, in which the input is the CAD representation of the component, and the output is the additional knowledge gained of its performance from simulation of forces. Part (3) shows a task in which multiple application-type entities form the input for a task that produces a single information-type output, and illustrates that multiple entities have potential to act as both inputs or outputs to a task.

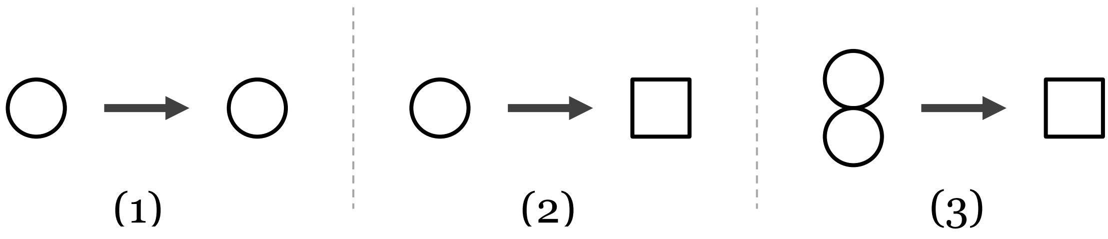


Figure 20: Transformations between entities as tasks

Note that there is no process of the designer implied by these diagrams; only the use of one type of entity as input, and another as output. These images therefore are illustrative of transformation types, but not of how transformations are completed.

Figure 21 shows a real-data example of a task transformation. The *behaviour* entity at the onset (a description of the bending behaviour of a component when loaded by the system) is used as a basis for calculation, which produces a discrete *knowledge* entity (the stress and deflection within the loaded component). Note that further examples of coding can be seen in Chapter 7 and Appendix IV.

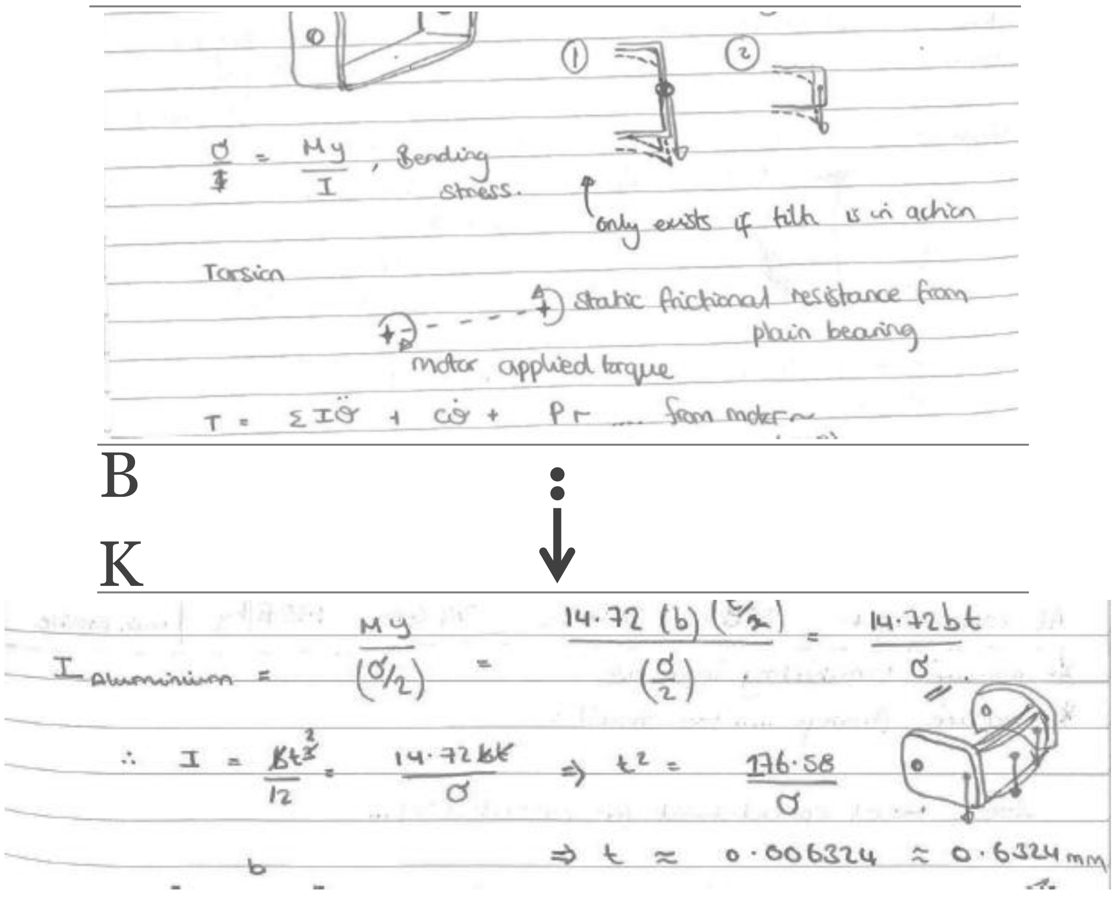


Figure 21: Real data example of task transformation, from study participant 1B

6.3.4 Types of Transformation

An assertion of the previous section has been that tasks are categorised by output, and so as being of an information-type or application-type. This description addresses the focus of each task by the output that it produces, and hence the focus of the designers' work.

In addition, as entities can be of two different types (information or application), a further method of categorisation is possible. When both the input entity and output entity are of the same type, this work describes the transformation as a *within-entity* task. When the input and output entities are of different types, this work describes the transformation as a *cross-entity* task (see Table 21). This classification is referred to as the *transformation type* within this work.

The value in this alternative method of classification is in what it describes. Classification by output highlights the focus of the designer in their individual tasks. Classification by within- or cross-entity highlights the manner in which the designer produces their output entity. Output classification describes what the designer is doing, while within- and cross-entity classification describes how they do it. Classification of tasks by transformation type therefore describes elements of the actual task process of the designer in each task that they complete. Relating back to Figure 20, part (1) is therefore a within-entity type task, while parts (2) and (3) are cross-entity type tasks. The ability to analyse both these categories then allows the coding scheme to study both the *focus* of tasks that designers tend to complete, and to analyse any patterns that appear in *how* they complete those tasks.

These two categories are mutually exclusive. An information-type task can have an input of either information or application entities; as can an application-type task.

Table 21: Transformation types

Task type	Description
Information	A task in which the output entity is of the information type
Application	A task in which the output entity is of the application type
Within-entity	A task in which the input and output entities are of the same type
Cross-entity	A task in which the input and output entities are of different types.

Table 22 provides more tangible examples of these task types according to their input and output entities. Note that the letter (I) is here an abbreviation for Information, and the letter (A) is an abbreviation for Application.

Table 22: Examples of tasks and classification by input and output

Task transformation	Output classification	Transformation type	Example input	Example output
I → I	Information	Within-entity	Partial material specification	Complete material specification
A → I	Information	Cross-entity	Representation of Individual component	Stress performance profile of component
A → A	Application	Within-entity	Partial system layout in CAD	General assembly drawing
I → A	Application	Cross-entity	Product specification document	Collection of functional concepts

6.4 Identifying Creativity within Tasks

The framework has so far described individual tasks through the entities that they contain. In studying creative tasks, the next step is to develop a process of identifying creative behaviour.

As is described in detail in Section 2.4, a creative act within the framework is recognised as and termed an act of *expansion*, in which the designer will attempt to identify new knowledge and variables (*information* type), or identify new ways in which present knowledge or variables can be used (*application* type). The term *expansion* is used within this work as synonymous to exploration. As the term explore is used frequently within creativity and behaviour literature, *expansion* here provides differentiation from other work, and clarification of when this work is referring directly to a property of the framework.

Creative actions are performed with a goal of promoting a creative result according to definitions within literature; a design that is novel, appropriate and unobvious (Howard et al., 2008a, Chakrabarti, 2006, Sarkar and Chakrabarti, 2011). In this sense a creative act can be tied to the purposeful goal of reducing clarity to the possible solution and understanding of the design decision to take by considering alternatives; a view corroborated by Dym's (1994) interpretation of non-routine design, and the tendency of particularly creative designers to treat problems as ill-defined, regardless of the actual level of definition (Cross, 2004b, Candy and Edmonds, 1997).

Creativity in either of the creative behaviours described by Gero (2000) and Dym (1994) are also described by this thinking. To introduce new variables or knowledge for the design requires exploration of knowledge or variables that have potential to be used. To understand how current variables and knowledge can be used in a new way requires exploration of the constraints and descriptions of each, and of the way in which they can be used.

To relate this interpretation to that of a more classical view, expansion refers to creative behaviour within both the divergent and convergent stages of Guilford (1956). Within divergence, when the purpose of the task is idea generation, creative behaviour is logical; the designer will usually attempt to produce some collection of alternative solutions. Convergence can also be creative (Cropley, 2006), in that the designer may attempt to form a single solution through alternative combinations of parts and systems, or may evaluate based on alternative criteria such as added functionality beyond the specification. Expansion within this work is then illustrated In Figure 22. As has been stated within Section 2.2, designer behaviour and design products that are interpreted as creative may vary according to the judgement of the observer. However, it is through the study of designer behaviour often found within creative processes, such as that studied within literature, that deeper understanding may be gained.

As antonym to *expansion*, the term *restrained* refers to any task in which the designer does not attempt to explore in any form.

The connection between creative behaviour and product should be noted. Within this work, there is no assumption made that creative behaviour will result in a creative product. The appearance of creative behaviour in the form of expansion can then be considered as behaviour that makes it possible for a creative product to occur, but does not demand it. Hence the terminology "promote a creative result" or "promote a restrained result" in Figure 22, and as used throughout the thesis.

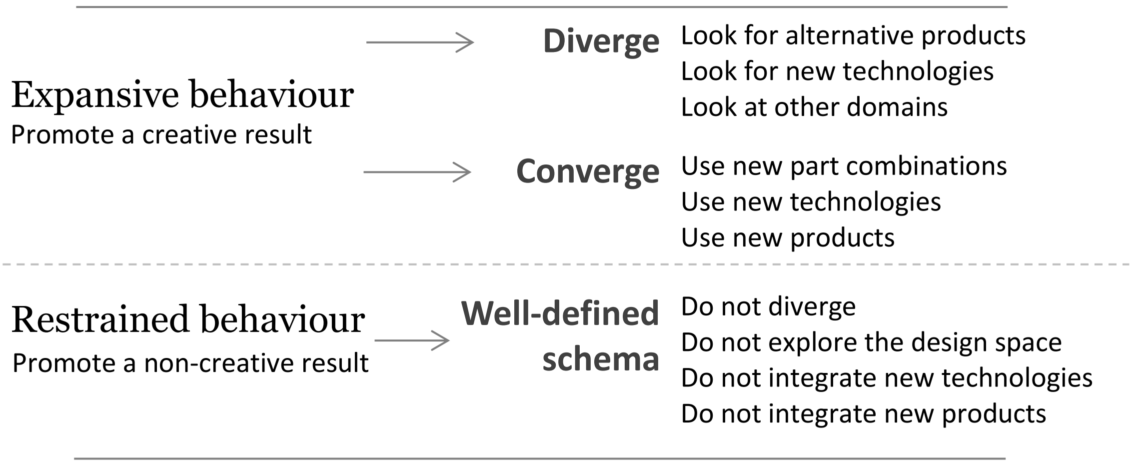


Figure 22: Creative behaviour through expansion

As illustrated within Figure 23, the appearance of creative behaviour can be signified through the appearance of expansion. In each part the task has been completed in a creative manner (indicated by a shaded output), resulting in an output that is either new to the design process, or represents an entity used in a manner not previously considered. Table 23 provides more tangible examples.

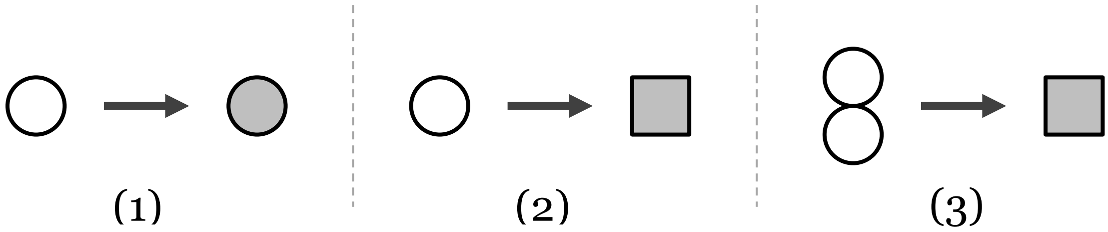
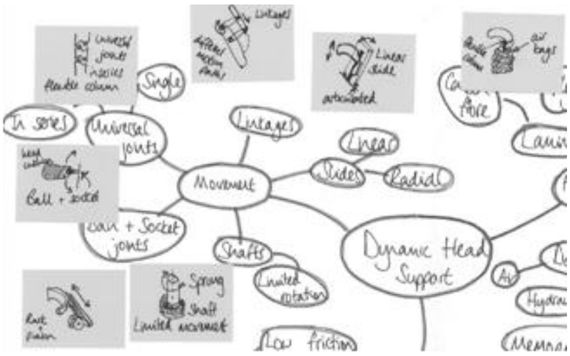


Figure 23: Visualisation of creative tasks

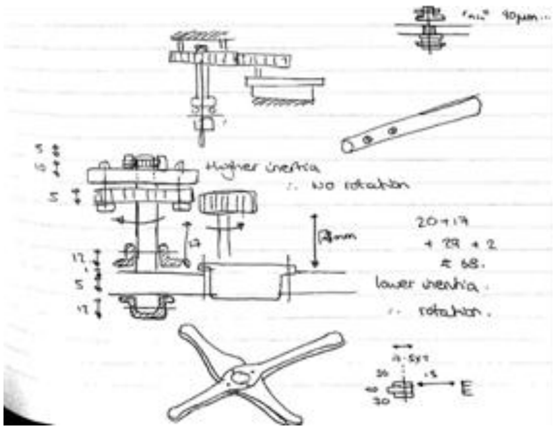
Table 23: Examples of creative tasks of varying input and output combinations

Input Type	Output Type	Creative Task Description
Information	Information	Based on required material properties, the search for and identification of a new material, previously not used for the function.
Information	Application	The production of several solution concepts, based on the initial specification.
Application	Application	The production of several layout alternatives for a sub-system.
Application	Information	The identification of new part dimensions based on stress analysis with, for example, the purpose of minimising mass.

Figure 24 provides a real-data example of an expansive and a restrained task. Note that Appendix IV contains an entire annotated script of coding from a study two participant.



An *expansive* task performed by designer D, in which the *Function* (Dynamic Head Support) is transformed into a collection of several working principles (examples of suitable *Behaviour*).



A *restrained* task performed by designer B, in which the *Behaviour* (gear/shaft) system) is transformed into a single *Structural Concept* (a structural layout), in a decisive manner without consideration of options.

Figure 24: Real-data example of an expansive and retrained task, from study participants 1D and 1B

6.4.1 Creative and Non-Creative Tasks

This framework then allows identification of tasks and of creative behaviour, both by entirely separate means. This removes any potential bias of certain types of task being considered as "more creative" than others, and also allows the assertion that different designers may complete the same task in either a creative or non-creative way.

Through the discussion within Section 6.3, several descriptors of tasks have been identified. There are two different types of entity (information and application), stating the focus of the designer; tasks can be either creative or non-creative; and tasks can be either within-entity or cross-entity, giving an indication of the manner in which tasks are completed. These descriptors can now be used to formulate each type of task that a designer can complete within their design process. As each category of descriptor is independent of the others, tasks can be one of eight different types, as shown in Table 24 with examples in Table 25.

Within this thesis tasks are generally described in terms of their entity transformation or output as has been described. For coding purposes however, each entity is listed as information-type or application-type, with the transformation shown as an arrow linking the two. As example, a task with an *information* entity input and *application* entity output is described as an [I → A] task. This notation is needed during the coding process itself, as the researcher must identify individual entities and determine those that form input and output. This level of detail is not required for analysis.

Table 24: The eight different task types

Entity transformation	Task Type	Creativity of task	Transformation type
I → I	Information	Creative	Within-entity
I → I	Information	Non-creative	Within-entity
I → A	Application	Creative	Cross-entity
I → A	Application	Non-creative	Cross-entity
A → A	Application	Creative	Within-entity
A → A	Application	Non-creative	Within-entity
A → I	Information	Creative	Cross-entity
A → I	Information	Non-creative	Cross-entity

6.4.2 Creative Approaches through Types of Task

Behaviour within this work is described as the sequence of tasks, implying the importance of patterns in tasks, and those that appear in majority and minority. This work also describes the *approach* of the designer as the manner in which they complete their behaviour, and hence as some characteristic of the patterns that each designer's process includes.

Due to the focus on creativity, the primary approaches determined here are recognised by a majority in information-type creative tasks or in application-type creative tasks. These are termed an *astute* approach and an *effectuating* approach respectively; both new terms which have no intended connotations in literature. In other words, an *astute* designer is one who is more often creative in information-type tasks, while an *effectuating* designer is one who is more often creative in application-type tasks. As such, both the astute and effectuating approach are implicitly linked to the occurrence of creative tasks.

Table 25: Examples of the eight different task types

Entity transformation	Creativity of task	Approach Type	Example
I → I	Creative	Astute	Search for materials with properties applicable or appropriate to expected solution possibilities.
I → I	Non-creative	Regular	Refine knowledge of certain materials e.g. database lookup of material properties for specific application.
I → A	Creative	Effectuating	Develop a number of potential sub-system configurations based on behavioural and functional requirement.
I → A	Non-creative	Standard	Configure a layout for components within a sub-system according to past design iterations.
A → A	Creative	Effectuating	Explore possible configurations or dimensions of components to reduce material use without compromising performance.
A → A	Non-creative	Standard	Parametrically alter dimensions for a component to allow interface within a sub-system.
A → I	Creative	Astute	Perform analysis of components within a sub-system to infer potential redundancy and reduce part count.
A → I	Non-creative	Regular	Perform stress analysis of a component to understand force and performance requirements of system/sub-system.

With these approaches, it is possible to visualise the framework by which these two creative approaches in design behaviour can be identified, seen in Figure 25. It should be noted that the order of stages in this figure is representative of the order that occurs during the coding process. In reality, as each category is independent, creativity of tasks and task type can be in identified in either order.

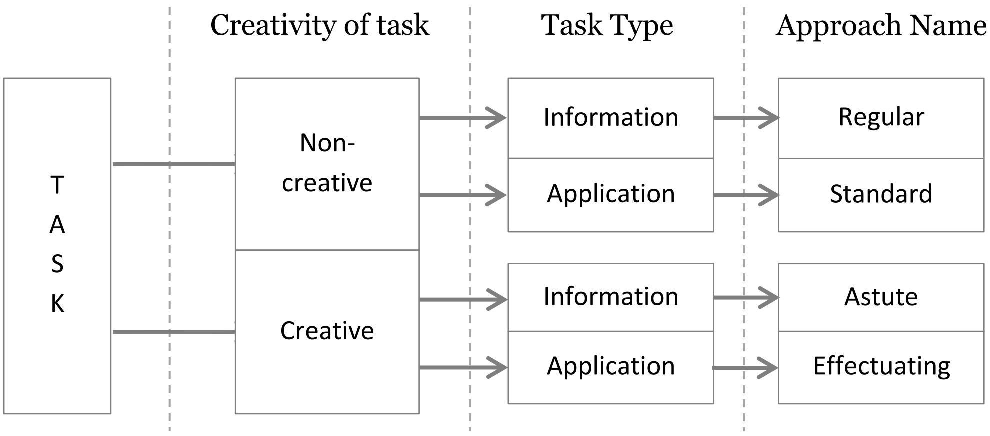


Figure 25: The framework for creative design approaches

The framework also presents two terms for non-creative approaches, *regular* when a majority of information-type non-creative tasks are completed and *standard* when a majority of non-creative application type tasks are completed. These terms are used solely to provide distinction between the two categories and (as they are non-creative) are not a primary focus within this work.

6.4.3 Creative Approaches through Transformation Type

As tasks can be categorised in two different ways, either by their *output* or by the *type of transformation* (see Section 6.3.4), a second framework can also be formed. This framework is shown in Figure 26.

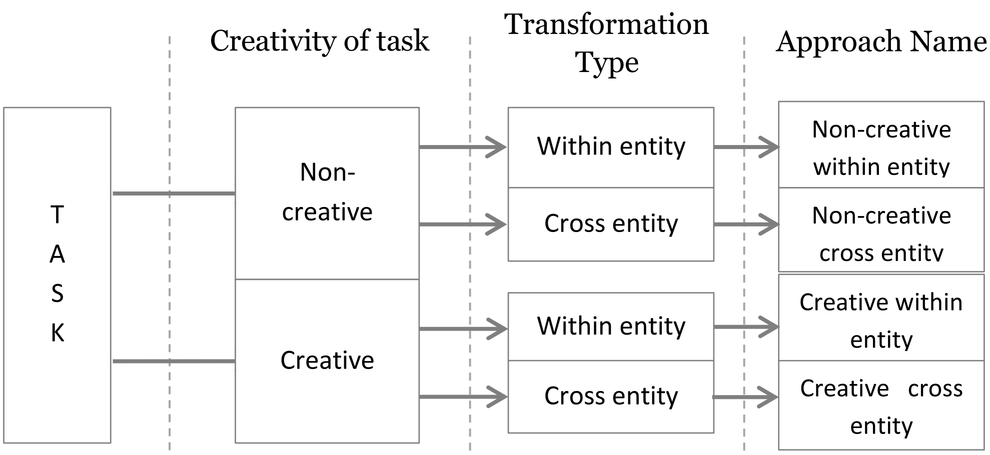


Figure 26: The framework for transformation-type approaches

To prevent the introduction of too many terms, approaches described by type of transformation and creativity are not given individual terminology, and will be referred to explicitly and in full at all points within this work.

6.5 Determining Behaviour from Tasks

Behaviour is described by a sequence of tasks, and therefore implies a time dimension. To analyse behaviour it is then necessary to study multiple tasks occurring in sequence and as part of a designer's process. Through analysis of patterns that appear in their sequence of tasks, it is then possible to gain deeper understanding of their behaviour; particularly, through the coding scheme, with consideration of creative behaviour.

As illustrated by Figure 27, each part can be considered one task within a greater process. The process shown contains four tasks, two of which are completed in a creative manner (part 1 and 4), two of which are cross-entity type (2 and 3), and one of which is application type (part 1).

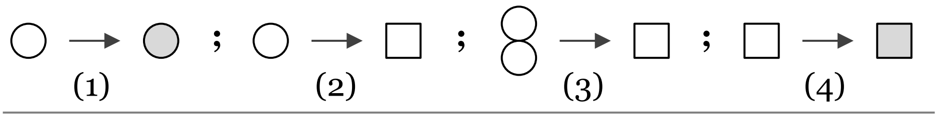


Figure 27: Design tasks as a sequence of entities

6.5.1 Determining Design Stage

There is one final element that must be understood before analysis can occur; the stage of the design process at which any task occurs.

In Section 3.3, design stages were defined through focus of designers' activities, as seen in Table 26.

Table 26: The stages of the engineering design process

Design Stage	Definition
Analysis	Determine the desired and required functions of the system, for it to complete its purpose.
Concept	Conceive the system functions in detail through preliminary description of system behaviour.
Embodiment	Design detailed system behaviour through preliminary description of system structure.
Detail	Design and finalise system structure, and all aspects that may influence it.

This element of coding can be determined by the coder directly as they observe the designers work, by interpreting the purpose of the task as according to the definitions.

In visualisation this can be represented by distance from the time axis, where a higher distance indicates analysis or concept tasks, and the elements of the diagram move closer to the time axis as detail increases.

6.6 Summary: The Framework and Coding Scheme

The previous sections have described the formation of a framework and coding scheme designed to identify creative behaviour within the design process, as completed by individual designers. Taking primarily from the MOKA methodology (Klein, 2000, Stokes, 2001) and the work of Gero (1990), tasks are defined through a transformation of entities. Taking primarily from the work of Gero (1996) and Dym (1994), creative behaviour is determined through the use of knowledge and variables within the design process.

As this framework is based on literature, it can be considered valid in terms of the wider research field, a statement that will be reinforced through discussion of validity in Section 6.7. As the framework was developed through the use of a complete design record, which it is able to categorise in entirety, it is also valid for the data of analysis.

The framework proposes four primary approaches, determined by the majorities of types of task that the designers complete. These are summarised in Table 27. The approaches fall into two independent categories; both *astute* and *effectuating* approaches classify by task *output*; while both *within-entity creative* and *cross-entity creative* classify by *transformation type*.

Table 27: The four approaches of the framework

Approach	Description
Astute	Creative behaviour occurs primarily in tasks with an information-type output.
Effectuating	Creative behaviour occurs primarily in tasks with an application-type output.
Within-entity creative	Creative behaviour occurs primarily in tasks with input and output entities of the same type.
Cross-entity creative	Creative behaviour occurs primarily in tasks with input and output entities of different types.

6.6.1 The Elements of the Coding Scheme

To this point, the framework and coding scheme have been described with little differentiation between terms that belong to each; as there is a strong inter-relationship. For the sake of clarification, Table 28 lists those elements that are included within the coding scheme, and hence are utilised by the coder during the coding process.

Table 28: The elements of the coding scheme

Element	Use
Entities	The coder will identify individual entities within the work of the designer
Transformation	The coder will identify which entities form an input, and which form an output.
Expansion	The coder will identify any examples of expansion that occur as part of the entity transformation.
Restraint	The coder will identify whenever no expansion occurs through an entity transformation.
Design Stage	The coder will identify design stage, through the focus of the entity transformation and output entity.

It is these elements that form the coding scheme. Through their interpretation and analysis, the framework allows determination of approaches. The following sections now discuss the coding scheme in more detail; its validity, reliability, and actual methodological process.

6.6.2 The coding scheme and design thinking

As described in Section 4.1.2 and throughout Chapter 4, work on design behaviour and, to a degree, design thinking have been drawn from for the formation of the framework and coding scheme. It is therefore important to compare the tasks as identified by the coding scheme with the cognitive operations used within other research.

As introduced, design thinking considers four distinct cognitive operations; generation, evaluation, comparison, and selection. It is through sequences and combinations of these that the design performs their mental processes and by extension their design tasks. While behaviour as studied in this work and cognitive operations focus on different levels of abstraction it is worthwhile examining the relationships that can be inferred between.

The coding scheme presented within this chapter has been designed to study *what* a designer is doing, rather than *how* (from a cognitive perspective) they are doing it. To do this it uses a focus on output of tasks and the transformation that occurs as that output is formed as a differentiator between coding categories. Cognitive operations therefore occur on a higher level of abstraction to the coding scheme. Depending on the task, a single or sequence of cognitive operations may be performed which, individually or in summation, complete the individual task goal. Table 29 gives some examples of cognitive operations applied to each task type. The scheme has been developed in this manner in order to allow direct study of the task behaviour of designers and how their actions contribute to the completion of the goals of the wider engineering activity; in other words, identifying occurrence of tasks that occur within early and later-stage design (and occurrence of creative behaviour).

Table 29: Task transformations and cognitive operations

Task Transformation	Cognitive Operation	Example Task
I → I	Generation	Produce requirements or a specification for a particular brief.
I → A	Generation Exploration	Brainstorm ideas for a design that complete a certain functional principle, and form a set of potential configurations.
A → I	Comparison Selection	Analyse alternative design solutions to assess their capability to support loading, rank solutions based on loading capability, and select the most appropriate for further development.
A → A	Exploration Selection	Determine and finalise dimensions for a specific component based on a partial representation.

A future possibility from the work is then the study and comparison of the tasks completed by designers and the cognitive operations they use to complete such tasks. Just as different tasks have a possibility to be applicable to different stages of the design process, so do different cognitive operations have a possibility to be applicable to different types of task throughout those stages. In this sense, the detailed understanding of task behaviour of designers provides a strong and informative grounding for the study of cognitive operations within design, that can highlight when and where they are used, their impact, and the implications of their use and variation within certain tasks.

The framework and coding scheme within this thesis provide the means to study and develop understanding of what designers do within their design process. While research on cognitive processes highlight the potential for deeper understanding to be gained through future study, it is important before studying the detail of activity to identify and understand the activity that is completed itself; a goal that the framework and coding scheme fulfil.

6.7 Scheme Validity and Reliability

With any content analysis process, there are a number of considerations that must be made regarding validity and reliability. These are addressed in this section, and have also been separately presented in published work (Snider et al., 2012b).

Ensuring validity is the process of ensuring that the results are representative of reality. If the results cannot be said to be representative of the phenomena that the framework is designed to analyse, then no confident findings can be drawn from them. This also then concerns the validity of the context in which the results were gathered, to ensure validity in industry.

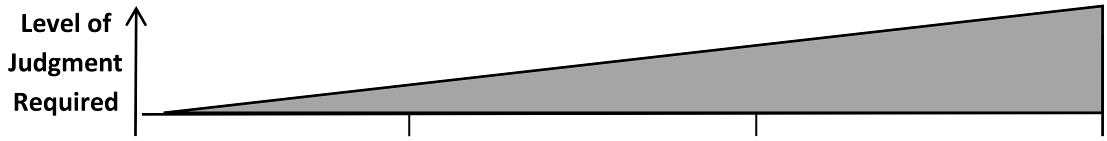
Ensuring reliability is the process of ensuring the framework and coding scheme consistently produce the same results and findings. Should different findings be produced on each application, then the implications of the findings cannot be considered accurate or robust.

One important note is that validity and reliability relate heavily to the coding scheme and the process of coding which, as it relies heavily on the type of data under analysis, is described within the study methodology (see Chapter 7). There are also validity concerns that relate to the type of data gathered and under analysis, which are also placed within the methodologies for each study.

6.7.1 Data-Type and the Role of Judgement

To ensure that the coding scheme identifies according to the purpose for which it was designed, it is important to determine the *type* of content that is being coded, and how any coders may interpret it. While the data itself may remain constant, the way in which it is coded may require the researcher to pass their own judgement of how it may relate to the scheme, or what it may mean in relation to the underlying theory. In cases such as this it is therefore important to create rules that provide direction to the judgements that the researcher may make, but it is equally important (in many cases) that the rules are not so rigid that judgement does not occur. In order to develop a scheme it is then important to understand the type of content that must be coded for analysis to occur (see Figure 28), the requisite judgement that coders must make to identify it, and hence the extent to which the rules may steer the coding and influence the coding schemes validity.

The type of data coded within the coding scheme presented here is known as *latent pattern* (Potter and Levine Donnerstein, 1999); in that precedence is put on the content of the data, and the belief that patterns can be found through recognising connections between the various entities that the coding scheme identifies. This process requires interpretation from the coder – it is their judgement that determines whether entities are important in each task and which entity leads to another. This is in contrast to manifest content, in which no judgement is required for analysis of the entities; and latent projective content, which is so judgement-based that the phenomena of interest are often the actual coding judgements themselves. To provide an example similar to Potter and Levine Donnerstein (1999); when coding people, manifest content would be that which is clear, such as the colour shirt they are wearing. Latent pattern content would then require some interpretation from the researcher, but would still be based on that which they can see, such as level of fitness; and latent projective content would rely heavily on the judgement of the coder, such as friendliness.



Type	Manifest	Latent Pattern	Latent Projective
Description	Interpreted according to clear rules, directly from the content of that which is being coded	Requires judgement of the coder. Codes that which is present on the page, but requires the coder to interpret its meaning and relationship to the final codes.	Requires judgement of the coder. Codes the judgements that the coders have made of the information that is presented to them.

Figure 28: The three forms of coding (Potter and Levine Donnerstein, 1999)

The effect of the type of data coded is that of its strong impact on the intertwining of reliability and validity. When coding manifest content, there is usually a specific correct answer for each entry. Accordingly, reliability can be ensured through the use of extensive rules, carefully constructed so that each entity can fall into only one category. Consistent results can then be produced, and will increase both reliability and validity as long as they are built accurately from theory.

The relationship between latent content and validity is more complex. The development of extensive rules will still increase reliability between coders, but as a result the validity will decrease. This is because, with extensive rules, focus is shifted away from the difficult judgements that the coder should make onto the conditions of the rules themselves; thus providing potential for the coding to shift away from the essence of that being coded (Potter and Levine Donnerstein, 1999). Validity must then be lower, with the scheme classifying according to specific and explicit features of the data rather than the important coder judgments that allow understanding of the underlying theory. A trade-off exists between reliability and validity in the development of the coding scheme; enough rules must be present to produce consistent results, without so many that coder judgements are no longer needed.

Within this research, the rules developed provide ways of classifying entities within tasks, but do not control how the transformation between them is interpreted. This is left to the coder, with examples of typical transformations from other data as a guide. Validity is then not sacrificed for the sake of reliability; assuming the scheme is developed correctly from theory all coders will make similar judgements, showing scheme reliability and that it classifies in the manner for which it was designed.

6.7.2 External Validity

To demonstrate that results are relevant in terms of existing literature they must demonstrate two characteristics. First, they must be able to demonstrate literature concerning each element of their formation, as described throughout the early sections of this chapter. Second, they should demonstrate some form of relevance to external literature that purports to analyse similar phenomena.

In this work, this second task is completed through comparison to the results of a creative style test similar to the Kirton Adaption-Innovation scale (KAI) (Kirton, 1976)(see Section 2.3). This scale has been chosen due to its relevance in subject matter, as it claims to categorise the way in which people will work with no connotations of design stage or situation. Hence it is process independent, and will produce results that are comparable across design processes, across designers, and across design situations. By measuring the KAI profile of participants within studies, and comparing to study variables, some conclusions of scheme validity and the nature of individual creative style can be made. The role of the KAI scale and its impact on validity are further discussed in Section 11.4.

6.7.3 Reliability

Reliability within a coding scheme refers to the consistency of the results produced from the data, when analysed by alternative researchers. Should a scheme be reliable, the same results will appear from the same data set regardless of who is performing the coding, and regardless of whether the data has been coded before. It is tested through the process of inter-coder testing, in which multiple researchers code the same data set, using the same rules. The results of this coding are then compared, and computed into a level of agreement that reflects the ability of the scheme rules to produce consistent results. The two important elements of demonstrating reliability are the assessment procedure and the analysis procedure.

The coder selection process

Care must be taken in the choice of coders used to test reliability. A high level of prior knowledge of the scheme may skew results through coding according to what the scheme *should* produce according to its purpose, but not necessarily according to what the scheme *would* produce if used by a coder without prior knowledge. It is therefore best to use independent coders that were unrelated to scheme development (Krippendorff, 1981, Potter and Levine Donnerstein, 1999).

This coding scheme tested reliability using the author who developed the scheme, and one additional coder who was hired specifically for coding (and hence was entirely unaware of the research project and its content). Ideally both coders would have been new to the framework, and more than two coders would have been used. However, as presented in here, suitable values for reliability were still achieved.

The coder training process

In order to appropriately administer the coding procedure, it is important that all coders are familiar with the rules of the coding scheme. This is particularly important when the scheme requires some judgement, and hence understanding of the underlying concepts must exist to some extent.

Training itself takes place through an iterative process of coding, assessment and re-definition designed to increase reliability within the scheme and the coders.

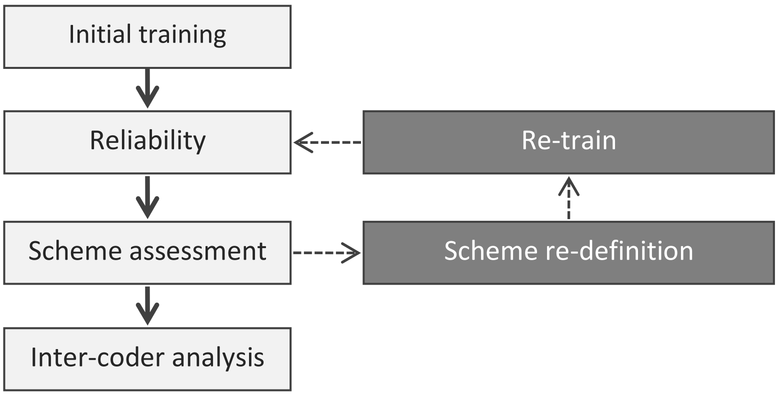


Figure 29: The training model used within this analysis, based on Krippendorff (1981)

For this coding scheme, the training process occurred according to the process within Figure 29, and is largely based upon that recommended by Krippendorff (1981). The initial training and reliability stages serve to introduce the trainee to the scheme in a more general sense, and to allow analysis of their interpretations of the scheme. This is then used in an assessment process, considering the accuracy of coding the trainee can provide and the various reasons by which their coding may differ from the expected, and from what is considered *correct*. Training occurred according to the steps listed in Table 30.

This process allowed the coder to gain sufficient relevant experience to provide a consistent and reliable result, while also highlighting and improving the coding scheme.

Table 30: The steps of coder training as performed for the coding scheme

Step	Description
1	Familiarisation of the coding scheme with the trainee, aimed at producing an understanding of the codes and rules themselves, and how they must be applied to the data set for analysis.
2	Preliminary coding of approximately 50 tasks from several logbooks; analysed for both overall reliability (Cohen's kappa and Krippendorff's alpha) and any reasons for disagreement.
3	Re-definition of coding terms to reduce ambiguity and the possibility of misinterpretation of data; followed by re-training of the coder.
4	Preliminary coding of one entire logbook containing 158 tasks; again analysed for both overall reliability and any reasons for disagreement, which were analysed on a case by case basis.
5	Further re-definition of terms to further reduce ambiguity; followed by retraining of the coder according to term re-definition.

An important danger that must be considered when refining a scheme in this way is that of the shared understanding of the coder and the trainees, stemming from the co-interpretation and analysis of disagreements. This shared experience allows a development of understanding amongst coders, such that the scheme can only be expected to be reliable and consistent among those who were involved in its development. Clearly, this effect must be minimised. Within this research, coder training occurred on a single researcher who was not involved in the development of the scheme, and had little experience in the subject area. This enabled the above concern to be controlled to an extent; their lack of domain knowledge allowed them to remain largely independent, and prevented them from heavily influencing the re-definition process beyond identification of ambiguity or areas needing attention.

Coefficients of reliability

Agreement itself is measured using a variety of metrics, computed based on the data produced by multiple coders studying an identical sample. Those typically used include percentage agreement, the number of times the researchers agreed as a percentage of the whole; Cohen's kappa (Cohen, 1960), which includes the possibility of the results occurring by chance; and Krippendorff's alpha (Hayes and Krippendorff, 2007), which includes the same, but is accommodating of a wider number of data types and number of coders. Of these, Cohen's kappa and Krippendorff's alpha are considered to be the better measures due to their consideration of chance; using only percentage agreement tends to produce a higher value, overestimating the ability of the scheme to produce reliable results.

Acceptable correlation values for these measures are typically taken to be above 70% (Klenke, 2008, Blessing and Chakrabarti, 2009).

The process of training and analysis

The inter-coding testing process itself occurred on a representative sample of data, forming approximately 10% of the total data analysed in Study One; a suitable quantity for analysis (Potter and Levine Donnerstein, 1999). This sample consisted of a 60% proportion of data that had not been previously been seen, and a 40% proportion of data that was assessed by the researcher as being of a particularly difficult-to-code format. As such, the coefficients of reliability should be considered a "worst-case" evaluation.

Due to practical constraints the process of training for this coding scheme occurred over five days, significantly less than the several month long process recommended by literature (Krippendorff, 1981). As a result, the re-definition and re-training phases of the process were completed to a less than ideal level, resulting in some ambiguity of the categories into which data should fall. Regardless, the achieved values for Cohen's kappa and Krippendorf's alpha of 0.770 and 0.768 respectively are considered suitable for exploratory research (Klenke, 2008, Blessing and Chakrabarti, 2009), and reflect the finding of Milne and Adler (1999) that adequate agreement can be reached with minimal training. Table 31 presents the intermediate reliability scores according to the procedure described in Table 30, and the modifications to the scheme made.

Table 31: Intermediate test scores for reliability of the coding scheme

	First Test	**Second Test**	**Third Test**
Cohen's kappa	0.497	0.678	0.768
Subsequent Modification	Development of stricter rules for the separation of tasks within the data. Determination of tasks themselves remains a coder judgement.	Increase detail of definition of "entities" within the data that coders can use to better judge task process. Relationship between entities defines task and is reliant on coder judgement.	No changes made – final inter-coder testing session.

6.8 Scheme Development Process

The previous sections present the framework and coding scheme through the literature from which it was formed and the elements by which it codes. They do not, however, exactly present the process by which the scheme itself was formed.

As mentioned, the scheme was developed through a combination of induction and deduction, using existing literature as a basis for its formation and a designer's logbook as reference to real data. By this method, validity of the scheme was encouraged in reliance on existing underlying theory and appropriateness for data that would be studied.

Actual development of the coding scheme occurred as according to Figure 30 and Table 32. Note that the development was an iterative process, in which the scheme was redefined both during the initial inductive stage using a designer's logbook, and throughout the coder training process. The coder training process itself occurred according to the process described in Section 6.7.3.

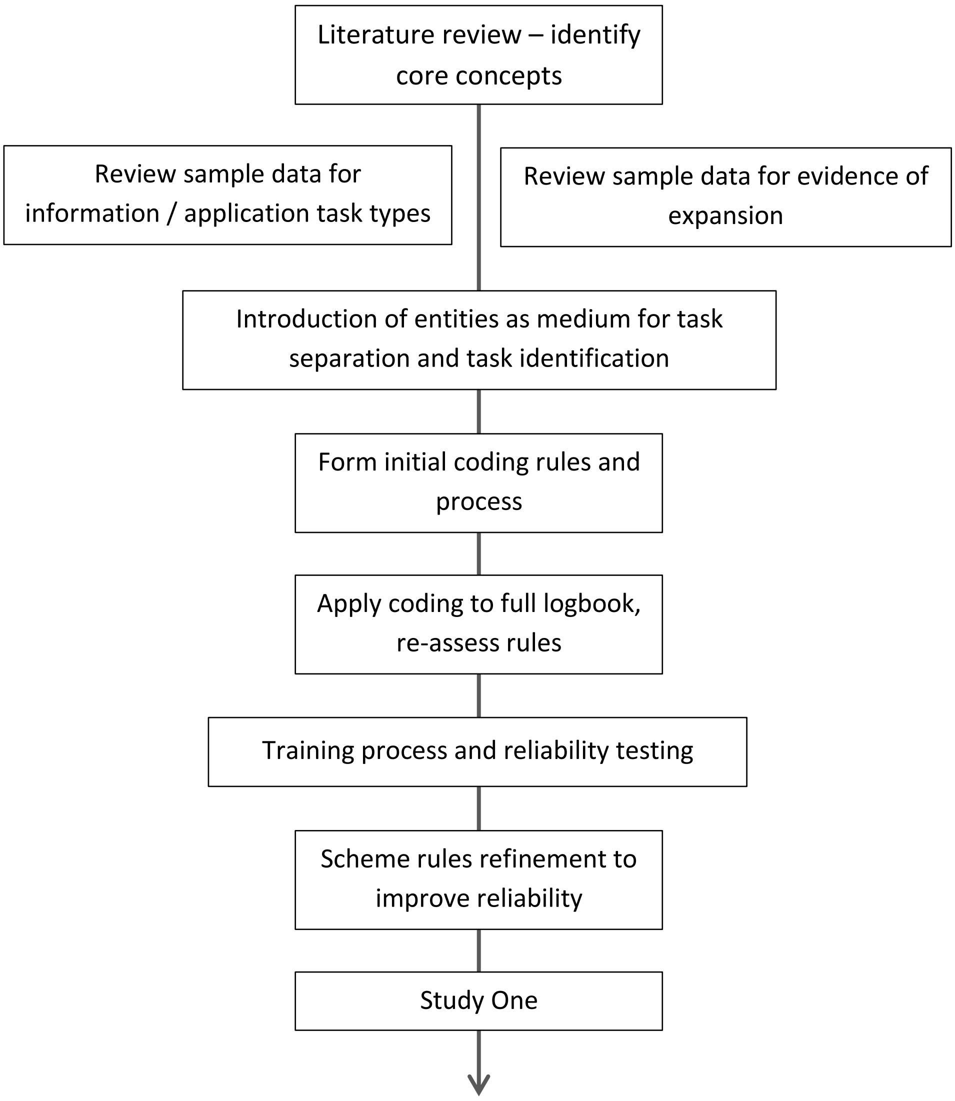


Figure 30: Coding scheme development process

Table 32: Coding scheme development process and stage description

Development Stage	Stage Basis	Description
Literature review	Literature – existing research	Identified concepts of task focus (information / application-type tasks) and expansion as an indication of creative behaviour.
Initial review	Designer logbook	Parsed example logbook recording a 22-week engineering design project, for indicators of information and application-type tasks, and for evidence of creative behaviour.
Entity introduction	Designer logbook	Developed understanding of task entities, and integrated into coding scheme as method of separating tasks, and of identifying task type as information or application.
Initial coding rules	Designer logbook	Formed complete coding process including all necessary elements.
Apply initial rules	Designer logbook	Complete pass-through of logbook in order to ensure complete classification of data and accuracy of coding. Re-define coding terms as appropriate.
Reliability testing	Real data	Initiated training process with a naïve coder, on unstudied real data. Training took place over one week and included approx. 200 identified tasks. Reliability testing occurred using Cohen's kappa and Krippendorff's alpha.
Scheme refinement	Real data	Re-define coding terms to improve reliability.
Study One	Real data	Use of coding scheme in real study.

6.9 Summary: The Framework for Research

The purpose of this chapter to this point has been to present the framework and coding scheme used in analysis.

The framework has been developed primarily through a deductive approach, although some inductive development was included through a design record of a single 22-week project, as completed by an individual designer.

The coding scheme itself identifies tasks through the entities that form their input and output, with a coder determining the transformations that exists between entities present in the data. The majorities and minorities of types of task present within the analysis of this data then determine the approaches each designer has used.

6.9.1 Effectiveness of the Coding Scheme

In Section 6.1, a number of criteria were set out, describing the requirements for the framework and for the coding scheme. Table 33 shows how these requirements are met.

6.9.2 Advantages of the Framework

There a number of benefits that the framework and coding scheme presented in this chapter provide, that are worth additional explanation.

First, the framework and coding scheme are appropriate at varying levels of granularity depending on data type and purpose. As within activity theory, tasks exist in a hierarchy including several layers of sub-tasks, down to the point at which the task is better described as a cognitive action of a designer. Particularly in context of the tasks describing designer behaviour, the coding scheme is capable of classifying at any level of detail that can be found within the data under analysis. Even to the point of describing process activities in the language of the framework, so long as entities are present in data, the coding scheme is applicable.

Second, coding occurs at a generally abstracted level, removing some elements of context sensitivity. There is no requirement throughout the framework or coding process to consider the project upon which the designer is working, the company and context of their working, or their personal knowledge and expertise. Such analysis need only occur when it is a fundamental part of the phenomena of interest (which is the reasoning for the inclusion of design stage analysis in this work). This lack of context sensitivity is useful when attempting to compare designers and their behavioural processes; as long as context is understood, designers can be directly compared.

For the same reason, the coding scheme also has wide applicability to a variety of design situations. Across a wide variety of designers, projects, and data types it is possible to perform effective analysis. Particularly due to the variation in company and product seen in industry, this wide applicability is seen as a strong benefit.

The coding scheme makes no assumptions of necessary connections between creative behaviour and creative product, and places a firm independence between creative behaviour and the design process in general. It therefore acknowledges that creativity is in a large part an individual phenomenon, that significant variation will exist in its appearance, and that the appearance of creative behaviour is distinct from the appearance of a creative product. Rather than assuming those connections, the framework and coding scheme is able to actively investigate their existence.

Table 33: The completion of framework and coding criteria

Requirement	How Acheived
Framework	
A primary focus on analysis of behaviour and process, rather than on product and output.	The framework analyses behaviour directly, through the tasks that designers complete. These are determined through actual occurrences, directly observed in their process.
Identification of creative behaviour within a designer's process, in contrast to non-creative behaviour.	The appearance of creative behaviour is determined through expansion.
Must be applicable across the context of engineering design.	No element of the context of design has any influence on the determination of designer tasks or creativity.
Must be applicable in all stages of the design process.	There is no influence of the stage of design on the determination of designer tasks or creativity. Design stage is identified separately by the coder.
The framework must be exhaustive in application.	All occurrences within the observed data can be identified as one of the entity types, and therefore as belonging to one individual task.
The framework must be applicable to a variety of data types.	Due to the abstracted nature of the framework, it does not rely on type of data for analysis. Any data that is representative of designer actions can be analysed.
Creative behaviour must be inherently linked, but fundamentally independent from tasks.	Creative behaviour and type of task are identified individually, by separate methods.
Coding Scheme	
Tasks must have definitive input and output.	All tasks are coded through the use of discrete input and output entities.
Tasks must be discrete in purpose and focus.	Each task can be described in terms of its output, and the type of transformation in involved.
Tasks must be exhaustive in classification.	All data can be allocated to an entity type, and hence to a task.
Tasks must be quantifiable.	Task categories are distinct and can be counted.
The coding scheme must be applicable to the work of individuals.	The coding scheme is designed to be applied to the work of individuals, and does not require the consideration of teams or groups.
Tasks must be independent of design process activities.	The coding scheme considers designer activity and design tasks to be separate, and codes designer tasks specifically.
The coding scheme must be applicable across different engineering processes.	The engineering context is not considered during the coding process.
The coding scheme must be applicable across design stages.	The design stage is assessed independently of task type and creativity, hence allowing comparison of such across design stages.

Chapter 7: Methodology: Main Studies

The framework and coding scheme presented in Chapter 6 form the means for the analysis of designer behaviour, specifically developed to address the research questions and objectives. Four studies have been performed as part of this process, chosen and designed to increase understanding of different phenomena of interest, as well as to complement the findings of one another.

As there are both strong similarities and strong differences between the performed studies, there is interest and understanding to be gained from direct comparison of their results. In order to enable this, results from studies one, two and three are presented within Chapters eight and nine, grouped according to theme; first those that relate to the general appearance of creative behaviour, second those that relate to designer behaviour through the stages of design. This format has been chosen to allow grouping of results for presentation and discussion – there are many similarities and balances between the studies, in which weakness in one is to some extent mitigated by strength in the other. This format allows these similar results and balances to be presented concurrently.

This chapter forms an introduction to these results, by presenting the methodology by which studies one, two and three were performed. It therefore lies within Section Two of the thesis according to the formal thesis structure Table 13.

As will be described in Chapter 10, study three continues for a slightly different purpose to studies one and two (that of study of the additional role of an industry context); and so is presented in its own right, accompanied with its own results.

7.1 Methodological Process

This chapter will present the first two studies completed, those that investigate the appearance of creative behaviour in later-stage design, first describing the general methodological considerations of each, and second presenting each study in detail. Following, an analysis process is described, used as an investigation into design quality of the results from studies one and two.

7.1.1 The Type of Study

For the purpose of descriptive study with an aim of characterisation of design behaviour, it is necessary to perform empirical observation of designers. While developed methods of analysis using means such as surveys (see the KAI scale (Kirton, 1976)) or contrived tests (see the TTCT (Torrance, 2008)) are able to produce robust results, they are also based on significant prior descriptive research. The understanding gained can then be developed and tested as prescriptive interventions. As observation study necessary in this case, there are some decisions to be made regarding the possible methods of observation.

There are a number of observational approaches available for study, such as study through logbooks and written records (see McAlpine et al., 2009, McAlpine et al., 2006, Eisentraut, 1997), protocol study (see Gero and Tang, 2001, Cross, 2004a, Akin and Akin, 1996), ethnographic study (see Ahmed et al., 2003), participatory research (see Howard et al., 2010), and reflective interview (see Björklund, 2013). Each of these has its place within research as a whole, with the appropriateness of their use depending on factors such as suitability to gather results, and wider research context.

Ethnographic study, a data driven approach in which observation occurs on a realistic setting without disruption of the designer, is an ideal approach due to its inherent validity for industrial design. This is particularly true in contrast to approaches such as think-aloud protocol which, while widely used (see Ball et al., 1997, Cross, 2004a, Atman et al., 1999, Fricke, 1996), do often rely on the participant completing contrived tasks in an experimental environment. Ethnographic study is therefore considered to provide deeper understanding than laboratory protocol study (Ahmed et al., 2003). A goal in the studies presented here was then to increase realism to as high extent as possible, while still allowing comparability between participants and studies where appropriate and useful.

Study One (also referred to as the *logbook study*) was a longitudinal, retrospective observation based on the written records of the participants. Due to the use of final-year undergraduate participants for this study and the 22-week time frame, direct and recorded observation was not possible. Additionally, as the results of the project were of high significance for assessment, rigid and consistent control of participants working environment was not feasible. For this reason, although there are some questions over the validity of a self-written record as a study medium, the logbooks of the designers were the most appropriate data medium. This approach is uncommon in research, but not unheard of (see Eisentraut, 1997, McAlpine et al., 2009), and is explored further in Section 7.3.2. However, the particular strength of this method is in its realism of marking within the record. All were part of a genuine project of consequence to the participants, all occurred according to the participants' terms and in an environment of the participants' choice. As representative of their personal work, this method is therefore strong.

Study Two (also referred to as the *observational study*) consisted of a four-stage laboratory study, and was recorded directly through video, audio and screen capture. Although unrealistic in this sense, the brief presented a form of task of a familiar type to the participants; and although participants completed the study according to a strict schedule, the location of study was chosen specifically for realism (university environment for undergraduate participants, and industry environment for expert participants). In this way study two ensured situational realism by allowing the designers to work in a familiar environment (Harrison and Dourish, 1996) and design process realism (through the procedure completed within the study), at the cost of removing the study of realistic tasks.

The approaches used in each study are chosen on the grounds of the requirements for realism and validity. In order to enhance these to a higher level, each study was completed in a familiar or realistic environment, at a cost in other areas. For study one, this is in confidence of data as a complete and representative record of design process; for study two, this is in realism of the task and design process in contrast to industry. Due to the different strengths and weaknesses of each, these two study approaches balance and inform each other to an extent, thereby increasing confidence in results as a whole. This is discussed in Section 7.5.

7.2 Selection of Participants

Clearly, the selection of participants impacts the validity of findings greatly; with much effort expended in literature on the differences between novices and experts (see Ahmed et al., 2003, Chi, 2006, Ericsson, 1996), (see Section 4.2). Within this work, as all participants were immersed in the engineering field, those typically termed "novices" are termed "experienced". This terminology is used to reflect the fact that all participants had undergone several years of formal training in the field, and so were not truly "novices" in either design or engineering. However, it also acknowledges that many participants were not expert (referred to as non-expert), and could not be expected to display expert performance. Expert participants were those with 10 years or more experience in the field (Ericsson and Lehmann, 1996), who can be expected to demonstrate better practice, leading to better results. This is a commonly held assumption within literature, but is not to be taken for granted. Accordingly, through the study of quality and creativity of both experts and novices as is performed in Section 8.7 and 9.7, this assumption is to be validated in the context of this work.

As with methodological approach, choice of participants for studies one and two was based largely on feasibility. In the case of study one the use of undergraduates was most feasible; they were working on one project alone and were easily recruited. In order to increase validity, study two used expert designers in combination with undergraduate and graduate designers. This allowed analysis of both experts and non-experts. Further detail of study participants is given in each studies detailed description.

7.2.1 Context of Study

The context surrounding the behaviour of designers has been mentioned as important at several points within this work. This is no different in the context of methodology. In this case, context then refers to such factors as participant experience, participant activity, participant environment, the design situation, and design requirements.

In relation to activity, and given that the majority of working occurs within the designers' personal computer or logbook (McAlpine et al., 2011), it is important that any recording procedure is capable of observing such sources, does not disrupt their working practice beyond that required for the study, and that designers are comfortable working under study conditions.

In addition to this, there must be awareness of factors relating to designer background and experience and their influence on study results. Primary in this work is the role of expert performance in comparison to performance of experienced participants and the inherent variation that results. Care must be taken that such variation is considered carefully and does not invalidate results, a subject that is addressed within Chapter 10.

Finally, in a case where two quite different studies are to be compared directly, the context of each must be understood. To allow comparison in a fair and appropriate manner, it must be clear at which points the studies are similar and different, the extent to which comparison can be made, and the subjects on which comparison can be made. Table 34 lists comparisons of this nature between studies one and two.

Table 34: Contextual similarity between study one and study two

Criteria	Study One	Study Two
Design process completed	Project from initial brief to working proof-of principle prototype.	Brief from initial information search to review of detailed design
Subject of design task	Design of physical product requiring engineering design.	Design of physical product requiring engineering design.
Project consistency	Different projects for each participant	Identical projects for each participant
Design process stages included	Requirement for design belonging to each design stage in order to complete.	Designers prompted to complete tasks belonging to each stage of design through study set up.
Participant surroundings	Designers working in their choice of surroundings	Designers in familiar working surroundings. University for non-expert, industry for expert.
Timescale	22 weeks	Four hours

In each of these studies, designers follow a personal design process to design a physical product. The product is of a form that is familiar to engineering design, as opposed to product or aesthetic design, and includes a variation in project for each designer (study one) and an identical project across designers (study two). Although the design process was not completed to an identical extent, in both studies designers completed tasks that can be described as of similar design process stage, and of similar process activities. These similarities allow collation of certain findings between studies, including individual designer behaviour and the appearance of creative behaviour, at points in which stage and process are similar. Further, the differences between studies allow direct comparison of the same or other findings when appropriate, such as the role of project brief on the appearance of designer behaviour. Further discussion of cohesion between studies is given in Section 7.5.

7.2.2 Study Process

The general method of each study shared many similarities, and can be broken down into three fundamental phases, described below. Further, Figure 31 demonstrates the process of study and coding for both studies one and two, and the differences between each.

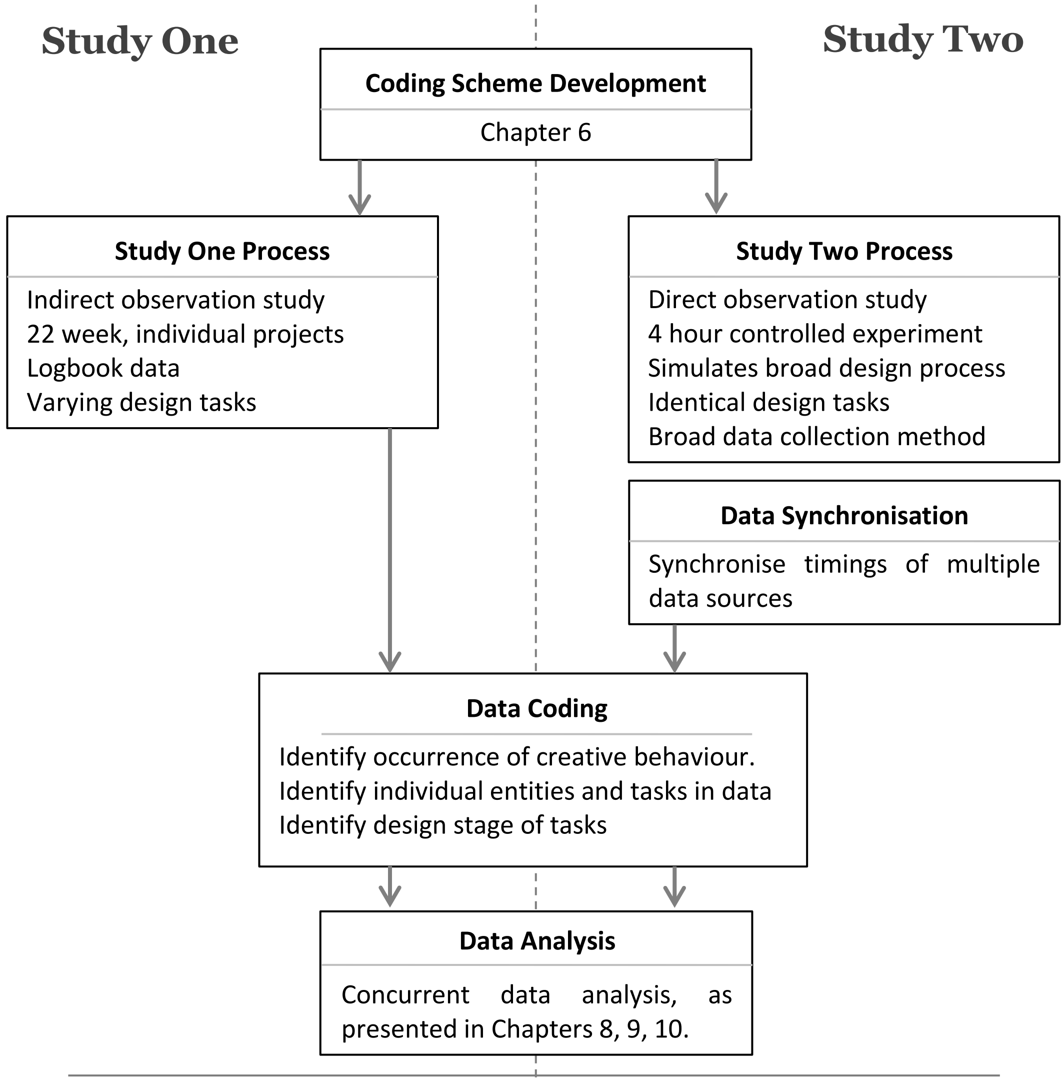


Figure 31: Process of studies one and two

Stage One: Data capture through observation.
Each study captured data through different means, detailed in their respective sections (Section 7.3 and 7.4).

Stage Two: Coding process
With the exception of initial interpretation of data, the coding process for each study was identical. It consisted of three steps which, due to the separation of coding criteria within the framework, could be completed in any order. For consistency in results, the coding process for each study consisted of:

Step 1 - Identification of occurrence of creative behaviour through expansion

Step 2 - Identification of individual entities, and subsequent task identification.

Step 3 - Identification of design stage of each task.

For each participant data set, these three steps occurred in three separate passes to maintain focus, in one sitting where possible, and at very least sequential participant-by-participant basis.

Stage 3: Data analysis
Analysis occurred through collation of quantities of findings in each category, and subsequent numerical analysis techniques where appropriate. As the coding scheme produces results at a level of granularity dependent on the data itself and is subsequently generalised, the analysis process is initially of high detail, followed by more abstracted results.

7.3 Study One – Logbook Study

The first study reported within this chapter was performed primarily for the purposes of validation of the applicability of the framework and coding scheme. However, as will be presented in Chapters eight and nine, when used appropriately and in comparison with study two, study one also allowed the development of findings. This study has also been presented in published work (Snider et al., 2013a); from which the following chapters present a significant development of results.

As such, the research aims of study one were:

"To investigate and demonstrate the validity and usefulness of the framework and coding scheme developed for the purpose of studying creative behaviour in later-stages of the engineering design process."

"To gain understanding of the appearance of creative behaviour in later-stage design tasks, with particular reference to creative approaches as defined from literature."

7.3.1 Study One Participants

Study one involved seven final-year undergraduate designers at the University of Bath, each completing a Specialist Design course. As the fundamental core of this course, the participants were required to design a product in answer to a given problem statement to be presented after development in the form of a working proof-of principle prototype.

Each participant had completed identical higher education and, of the seven, three had completed 12 months experience as part of an industrial placement. Each was free to complete the design process at will, although all had been familiarised with well-accepted design approaches such as Pahl and Beitz (1984) and Pugh (1990) as part of their teaching.

7.3.2 Study One Process

The coding scheme was applied to the work of each participant over the entirety of individual 22-week projects, each of which addressed a different problem statement. Although not a large sample size, through the detailed analysis of the working process of designers valuable and interesting results have been produced within much research (such as (Ahmed et al., 2003, Dorst and Cross, 2001, Akin and Akin, 1996)).

The purpose of the study here is two-fold; first to demonstrate usefulness, validity and reliability of the framework and coding scheme, and to present early results and conclusions; a goal that the data gathered is sufficient to achieve. Second, more detailed findings can then be produced from appropriate comparison with analysis of the data from study two, creating a combinatory data set with significantly more participants.

Each project consisted of a significant part of the design process, from initial task clarification to the construction of a working, proof-of-principle prototype. These projects varied between designers, but all followed the same requirements and structure as shown in Table 35.

Table 35: Structure of study one

Weeks 1-11	Weeks 12-22
Stage 1 Develop problem understanding	**Stage 4** Develop final concept
Stage 2 Perform background research	**Stage 5** Manufacture proof of principle working prototype
Stage 3 Report research and in-depth specification	**Stage 6** Full report
Assessment	Assessment

Source of Data

Coding occurred through the use of the student's logbooks, which they were instructed to use as a working document and complete record of the design process, and also formed part of the assessment process. As such, the logbooks contained a substantial amount of data taking the form of, for example, lists and explorations of potential requirements and constraints, lists of suppliers, descriptions and analysis of competitive products, sketches of configurations, geometry and dimensions, lists and sketches of individual components, brainstorms and mind maps, assembly diagrams and detailed dimensioned drawings of components for production. Within such data there is much evidence of the individual entities defined within Section 6.3.2, which can then be coded as tasks. For example, a dimensioned component sketch is likely to be coded as a *structure* (S) entity, and a table of material properties is likely to be coded as a *knowledge* (K) entity. Examples of data can be seen in Figure 32, with annotated coding in Figure 33 and a full annotated script (of study two data) in Appendix IV.

Engineers logbooks are a good record of the process followed, in terms of the chronology of recordings within (McAlpine et al., 2006), and due to the reliance of undergraduates on hand-drawn representations (Sobek, 2002). However, while logbooks capture a large amount of the expansive idea generation process (Currano and Leifer, 2009), they will not necessarily capture all tasks that occur. For example, while initial dimensioning tasks may be drawn, the logbook will not capture any evolution of these dimensions that occurred during any computer-aided design process. When gathering data, seven logbooks were chosen from a sample of seventeen. This was necessary, for practical reasons, in order to: remove logbooks that were illegible; showed little evidence of developing work (thus suggesting a logbook that was written after the design process as a reporting tool rather than as a record of the design process); or with little overall content (suggesting that the designer completed the majority of their work in other media). Although a limitation of this work, this is not thought to significantly affect the results and analysis gathered as evidenced by similar results gained from further study in which such discrimination did not take place (Snider et al., 2012a).

While alternative methods of data collection such as observational study or protocol analysis (see Blessing and Chakrabarti, 2009) may have provided a data set that could be treated as complete with confidence, they were considered impractical in this case due both to the difficulties in capturing reliable data (Gero and Tang, 2001) over the long duration and the limiting effect it may have on the working styles of the undergraduates.

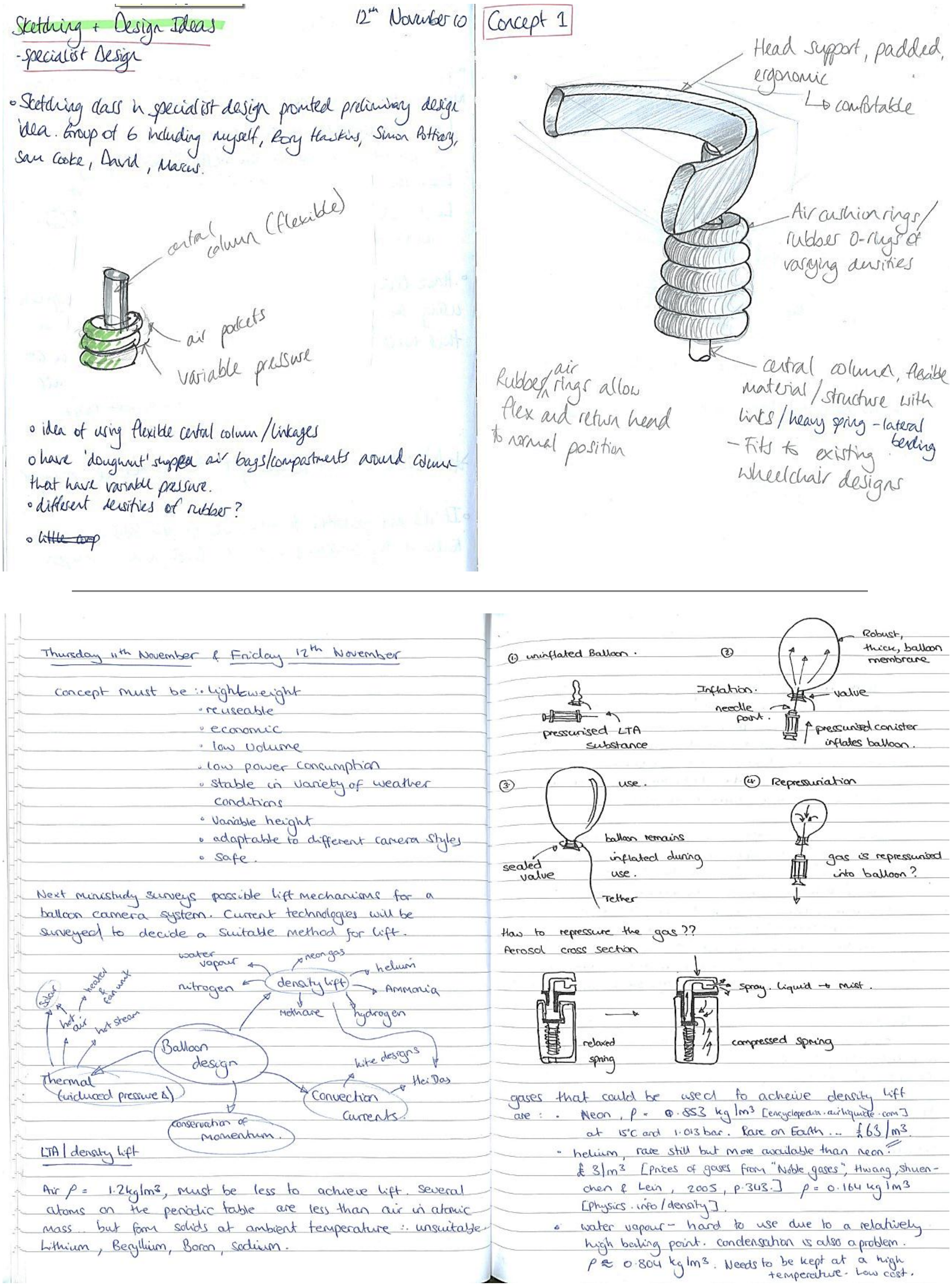
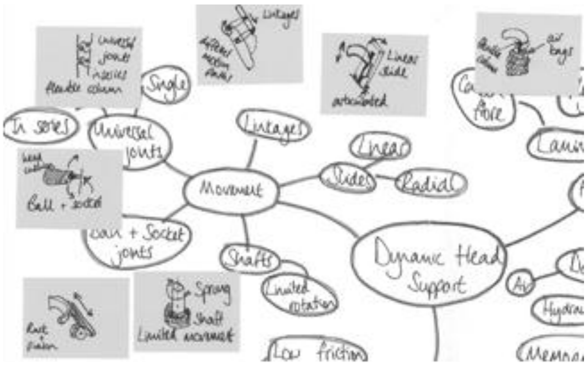
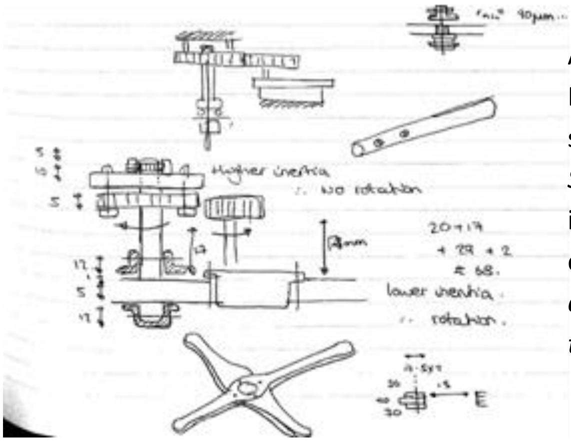


Figure 32: Example logbook data; Above, Participant 1D; Below, Participant 1B



An *expansive* task performed by designer D, in which the *Function* (Dynamic Head Support) is transformed into a collection of several working principles (examples of suitable *Behaviour*). Hence an *Information*-type entity to *application-type* entity transformation:

I → A transformation



A *restrained* task performed by designer B, in which the *Behaviour* (gear/shaft) system) is transformed into a single *Structural Concept* (a structural layout), in a decisive manner without consideration of options. Hence an *application-type* entity to *application-type* entity transformation:

A → A transformation

Figure 33: Example of data from Study One

Specific Coding and Analysis Process

The coding process itself occurred according to the procedure described within Section 7.2. Specifically for this study, data was interpreted by systematic review of each designer's logbook, reviewed in three separate passes. Although the time required for coding was too great to allow each to be completed in a single sitting, each logbook was completed in entirety before the next was started.

Additionally, each designer completed a creative style test similar to that of the Kirton Adaption-Innovation scale (Kirton, 1976). This allowed further analysis and validation.

Later-stage design in study one

As the focus of this work is on later-stage design, it should be made explicit how this was analysed. No influence was placed on the process of the designer during this project, they could perform any task at any level of detail as they saw fit.

Following the logic of Chapter 3 then, later-stage design could be defined as any task that concerned development of detailed system behaviour and detailed system structure, but excluded any elements of preliminary problem analysis or any determination of system function. Later-stage in the context of study one then does not consider time of occurrence or level of system hierarchy in any way – later-stage type tasks can occur at any point and on any system.

It should be noted that in reality distinction of design stage is also a highly context dependent judgement, and hence was in part reliant to the judgement of the individual coder, as with the determination of task type and creative behaviour.

7.3.3 Study One Summary

Study one was performed for two purposes. The first of these acts as a validation case for the framework and coding scheme proposed within Chapter 6. The second, in conjunction with results from study two, acts to provide useful results. The particulars of the study itself are summarised in Table 36.

Table 36: Particular details of study one

	Description
Research Aims	*"To investigate and demonstrate the validity and usefulness of the framework and coding scheme developed for the purpose of studying creative behaviour in later-stages of the engineering design process."* *"To gain understanding of the appearance of creative behaviour in later-stage design tasks, with particular reference to creative approaches as defined from literature."*
Participants	Seven undergraduate, final-year, non-expert engineers.
Team working	None
Length	22 weeks
Study Brief	Varied. Study of actual projects as part of degree course
Data	Logbook, kept as course requirement

7.4 Study Two – Observation Study

Study two was performed as a significant extension to study one, to investigate initial directions for research in more detail, to alleviate study limitations, and to provide additional understanding of expert designers.

It occurred through a direct observation of designers as they completed a four stage design process, designed to mimic the real life design process as described by Hales (1987), as presented in other research (Cash et al., 2013). This study was completed in collaboration with another researcher, who has published detailed methodology (Cash et al., 2013), and has also been in-part published in its own right from the context of this work (see Snider et al., 2014).

Due to the process of study two, it served as both an extension and counter-point to study one (as will be explored in Section 7.5). Its primary purpose was to investigate in more detail the creative behaviour of engineers in later-stage design, following the understanding gained from study one. It therefore served to provide supplementary and comparable data to study one in a controlled environment, therefore increasing understanding of creative behaviour without the effect of unknown variables or those of unknown effect as present in study one. Further, as validity is to be demonstrated in study one, study two is able to allow increased focus on understanding to be gained. Its specific aim was to:

"Investigate the appearance of later-stage creative behaviour in a controlled environment, with a consistent design brief."

"Increase understanding of the appearance of differing creative approaches within later-stage design, and typical patterns in creative behaviour".

7.4.1 Study Two Participants

Study two included undergraduate engineers, expert engineers, and recently graduated engineers working in an industrial setting. The expert engineers can be expected to display expert performance due to their extensive time within the field, while each other group can be considered only "experienced" to varying degrees.

The 12 undergraduate engineers were all from the University of Bath, had identical higher education, and an average of 10 months industrial experience. The 4 expert designers came from two different companies, each with a high focus on engineering design, and had an average of 159 months experience. Also from an industry context, the study included two recently graduated engineers working within the second company. Although also industry engineers in the same setting as their colleagues, the graduate participants had insufficient experience to be considered experts in their field with an average of only 24 months industrial experience.

Each participant completed a background questionnaire to ensure similarity in background, replicated in Appendix I.

7.4.2 Study Two Process

Serving as an extension to the data collected within study one and point of comparison for results, study two was designed to be allow a similar, although highly-accelerated, design process. However, due to the weaknesses inherent in the methodology of study one (namely confidence in completeness of data, lower experience of participants, inconsistent design briefs, and lower number of participants), it was vital that study two allowed increased confidence in findings. For this purpose, study two took several methodological steps to ensure validity and robustness of results, as presented in Table 37.

Table 37: Methodological considerations in study two, as improvement to study one

	Description
Participants	Higher number of participants than study one
Participant experience	Combination of experience levels to allow comparison Inclusion of expert participants
Research task	Identical for all participants
Data collection	As complete as feasible, including audio, video, screen capture, and questionnaire data.

For the 12 undergraduates, the study occurred according to Figure 34 over a period of four hours, designed to mimic a complete design process as described by Hales (1986). Between each stage participants were permitted short, supervised breaks to prevent fatigue, during which they did not discuss the study. The primary area of focus within this study was Stage 3, in which the designers were prompted to individually complete later-stage type design tasks. The remaining sections were included for collaboration with other researchers, although they did provide some inherent realism to the study.

As the critical stage of the study is the third and the fourth is discarded in this work, the participants in industry did not complete the fourth stage of the study. To encourage participation they also underwent a shorter stage one (20mins); however, both stages 2 and 3 were identical for all participants.

Throughout the study, the brief was to develop a remotely operated mount to be placed underneath a balloon for amateur aerial photography, and was consistent between designers. The full brief is replicated in Appendix II. Within this research analysis occurred only on the third stage, during which the designers were to "*Develop an appropriate, feasible, dimensioned, detailed solution*" and were presented with several goals designed to stimulate later stage design activities (such as "*include all component dimensions*"). Any conceptual design stage tasks that did occur (as defined in Section 3.3) were omitted from analysis.

	Stage 1	Stage 2	Stage 3	Stage 4
	Information Seeking	Group Brainstorm	Detail Design	Design Review
Duration	**50 mins**	**50 mins**	**90 mins**	**50 mins**
Teamwork	Individual	Group	Individual	Group

Figure 34: The structure of the second study

In addition to data gathered through logbooks, as occurred in Study one, data was collected using a webcam to record a front view of participants, another to record a wide view, Panopto recording software to capture computer screens (www.panopto.com) and LiveScribe (www.livescribe.com) notebooks and pens to capture real time, detailed logbook data. This comprehensive method ensured that all actions and tasks completed by the designers were captured by multiple sources; a particularly important factor given the lower confidence in completeness of data taken from logbooks alone as occurred within study one. Examples of data can be seen in Figure 35, with an annotated example of task assignment in Figure 36. Note that in Figure 36, original coding markings can be seen, with letters indicating entities and red numbers indicating the time (in minutes) from the beginning of the study stage at which the entry was made. These time markings could be used in reference to the screen-captured video recording of designers working.

As with study one, all participants also completed a test similar to the KAI scale (Kirton, 1976). In addition, all undergraduate participants completed the Torrance Tests of Creative Thinking to allow analysis including personal creative level (Torrance, 2008).

Specific coding and analysis process

The coding process was largely similar to that presented in Section 7.2, with some differences due to the type of data collected.

As study two gathered written notes, these could be coded in the same manner as study one. However, the additional video footage, computer-screen capture and real-time playback of written communication added a significant amount of detail.

The first stage of coding then became synchronisation of data sources. Video files were played back in time through the use of Camtasia V8.0 software (http://www.techsmith.com/). Each video was transcribed with a written comment on the video content at ten second intervals, giving approximately 540 notes per designer. These transcriptions could then be directly compared to the written notes by the designers in real time.

Through careful study of both sources in tandem, evidence of coding criteria in direct relation to time of occurrence could be gathered and recorded. This was a highly time consuming process, in excess of fifteen hours synchronisation and coding per hour of collected data. Following coding, analysis could be completed in an identical manner to study one. Examples of raw data and coded data are given in Figure 35 and Figure 36, with an entire coded script in Appendix IV.

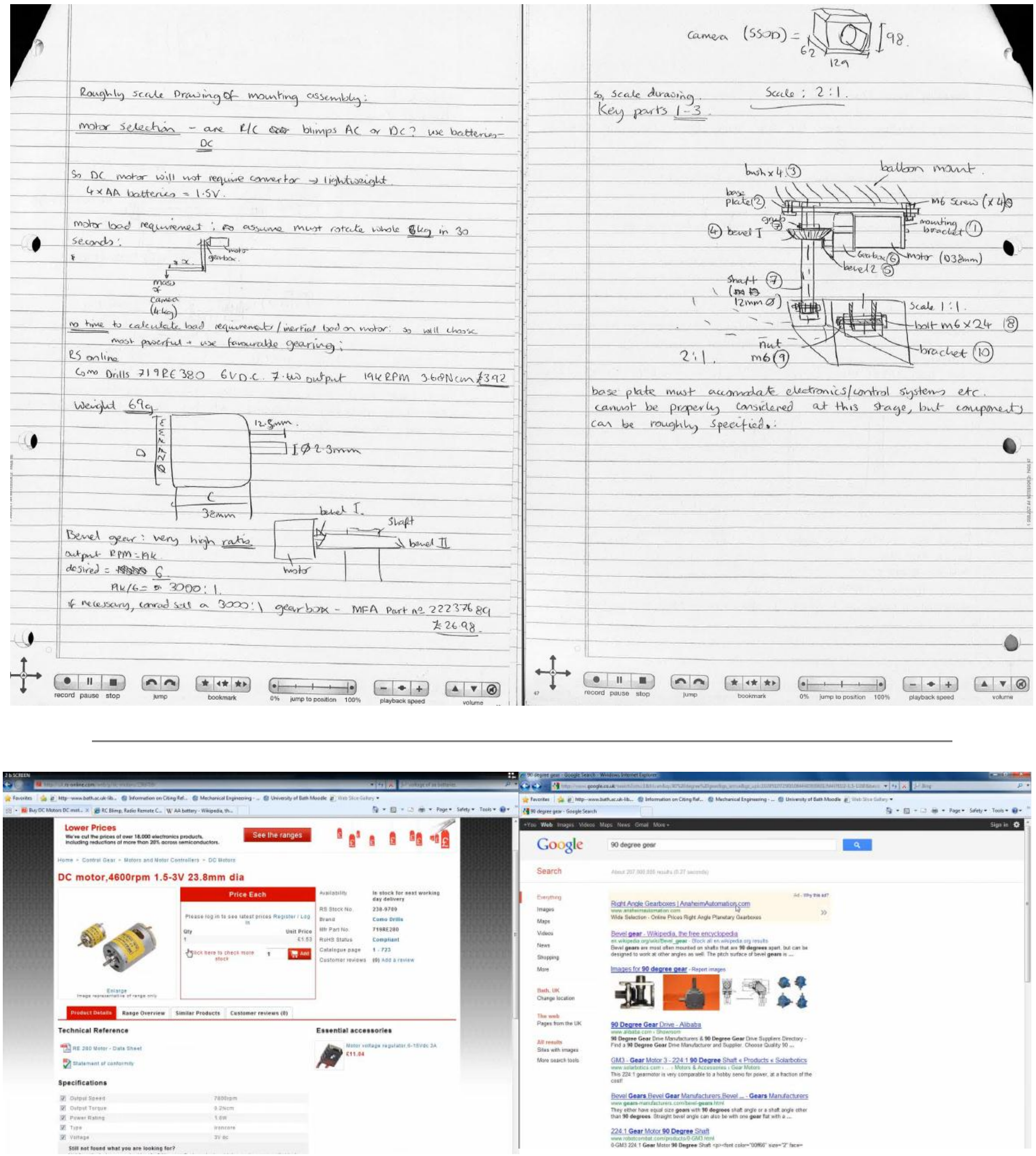
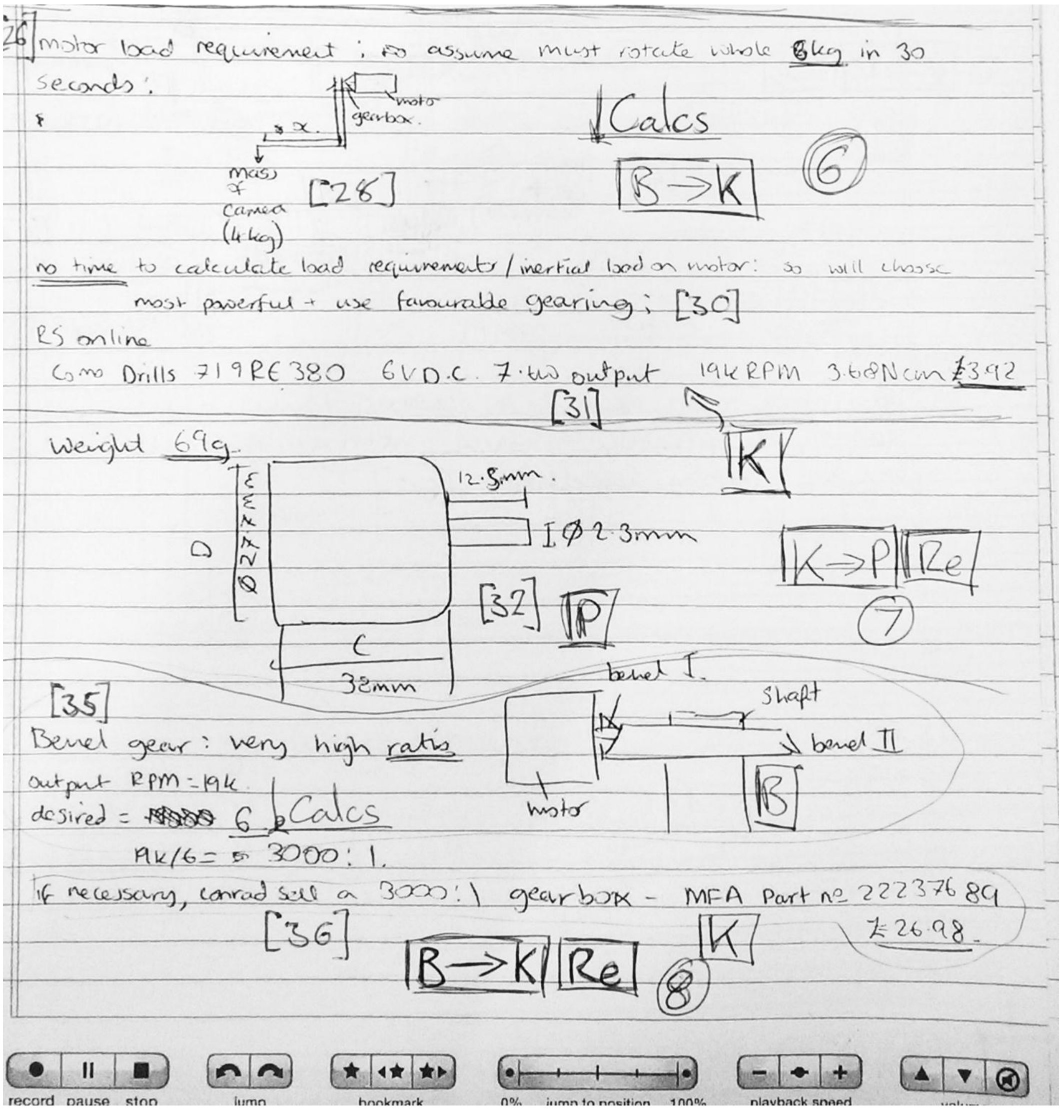


Figure 35: Examples of data from Study 2; participant 2E



Three identified tasks of participant 2E. As according to the coding scheme, tasks are separated focus of working.

Task 1 (labelled 6): Perform basic motor calculation (output of *knowledge* entity; K) based on system behaviour (input of *behaviour* entity; B). A single calculation completed on a single configuration with no optimisation; therefore the task is non-expansive. Task assigned as **B → K, restrained**.

Task 2 (labelled 7): Record dimensions of an appropriate motor (output of *structure* entity; S) based on results of previous motor calculations (input of *knowledge* entity; K). No searching or comparison occurred between motors, therefore the task is non-expansive. Task assigned as **K → P, restrained**.

Task 3 (labelled 8): Based on motor and its interaction with gearing (input of *behaviour* entity; B), produce requirements for the gearbox (output of *knowledge* entity; K). A single calculation with no optimisation or variations considered; therefore the task is non-expansive. Task assigned as **B → K, restrained**.

Figure 36: Annotated task example from Study 2; participant 2E

Later-stage design in study two

The structure of study two was chosen to prompt the completion of early stage type tasks in stage 1, and later-stage type tasks in stage 3. However, classification of design stage came from coding rather than location of occurrence within the study. Later-stage tasks were therefore considered only to be those that concerned later-stage design as defined in Section 3.3; any that were described as early-stage type were omitted. In practice, due to the study design, there were no cases of later-stage type tasks being performed in stage 1, and only a 16.1% instance of early-stage tasks in stage 3.

An additional note here is that the study included both an information seeking stage (Stage 1) and a detail design stage (Stage 3). Although not the primary focus of the study, the data gathered for stage one can also be coded and analysed, and allowed comparison of early-stage tasks between study one and study two.

7.4.3 Summary of Study Two

Study two involved 14 expert and non-expert participants, working on an identical brief within a controlled environment. The study itself involved both team and individual working, and mirrored the typical engineering design process. It was completed for the primary purpose of increasing understanding of the appearance of creative behaviour and creative approaches to behaviour within the later-stages of the engineering design process. Study two particulars are as presented in Table 38.

Table 38: Particular details of study two

	Description
Research Aims	*"To investigate the appearance of later-stage creative behaviour in a controlled environment, with a consistent design brief."* *"To increase understanding of the appearance of differing creative approaches within later-stage design, and typical patterns in creative behaviour".*
Participants	10 undergraduate, non-expert engineers. 4 industry, expert engineers 2 industry, non-expert engineers
Team working	1hr 40mins, although not studied
Length	4 hours
Study Brief	Identical for each participant
Data	Captured through audio, video, screen capture, logbook, background questionnaire

7.5 Summary of Studies One and Two

These two studies present the method by which a significant proportion of this research is completed. The purpose of each study is two-fold; first to provide data for analysis of designer behaviour within later-stage design, particularly that which is creative, and second to provide validation of the framework and coding scheme used for analysis.

The following two chapters present the results and findings from these studies, grouped by subject matter of the finding rather than by study content. Chapter 8 then concerns the appearance of creative behaviour, and individual creative approaches as demonstrated by each designer; and Chapter 9 concerns the occurrence of behaviour within later-stage design specifically and in contrast to early stage design. Discussion of the findings within these chapters is given in Chapter 11.

7.5.1 Cohesion of Studies

The relationship between studies one and two demonstrates both extension and complementarity. As an initial step, study one was completed to demonstrate validity of the framework and coding scheme used for research, and, should this occur, to provide initial findings that could be validated through further research. Through the study of engineering projects and through designer logbooks, study one is capable of fulfilling this aim (as demonstrated through the results Chapters 8, 9, and 10) but with some significant limitations (see Table 40). Study two then acts to counteract the limitations of study one through a higher level of control in study process – limiting the environment and task in which the designers work. As validity of the framework and coding scheme is demonstrated in study one, study two is able to focus more towards its individual aim and the aim of the wider body of research; to investigate creative behaviour within the later stages of the engineering design process. Due to the higher level of control, and yet similarity in terms of research and analysis approach, study two can both be used as an extension to and comparison case against study one, as described through Table 39 and Table 40.

A key element of these two studies is their complementarity and contrast, which allow both for strengthening of some findings and comparison of others (see Table 39). The benefit of this is that at points in which the studies are directly comparable, results can, with care, be combined. This effectively increases the size of the data set and increases confidence of results.

Table 39: Cohesion between studies one and two

Criteria	Comment
Complementary analysis	
Design stage	Design stages in each study were interpreted identically.
Creative behaviour	Creative behaviour in each study was interpreted identically.
Creative style/approach	Relating to analysis as will be presented, the creative approaches of each designer as interpreted from the data can be considered comparable.
Creative style test	All designers completed the creative style test, and so their behaviour in relation and correlation to it can, to an extent, be compared.
Task type	All task coding was identical in each study, and so can be collated for analysis where appropriate.
Contrasting analysis	
External influence	Study two occurred under time pressure, and according to the procedure of the study. It is hence not realistic to the same extent as study one.
Design completion	Designers in study two completed their design to varying degrees, dependent on their own working speed. They can therefore be compared to each other, but not to study one.
Participants	Study two used some expert designers, while study one used undergraduates.

Another benefit of these two studies is that they each partially mitigate the weaknesses of the other, as shown in Table 40. This balance is a particular strength, increasing confidence in results and validity in findings.

Table 40: Strengths and weaknesses of studies one and two

Study One	Study Two
Weakness: Only experienced student participants.	Strength: Expert participants and experienced student participants.
Weakness: Differing project briefs	Strength: Identical project briefs
Weakness: Lower confidence in completeness of data.	Strength: Complete observation of participants
Weakness: Lower number of participants.	Strength: Higher number of participants.
Strength: Realistic task completed freely by the designers.	Weakness: Lower realism in constrained setting and situation of design study.
Strength: Longer-term study	Weakness: Short-term study
Strength: Un-intrusive data collection method	Weakness: Disruptive data collection method

7.6 Analysis – Quality Evaluation

Upon the designs produced by participants in study two, an analysis process addressed the issue of quality of designs produced and how they may be tied to behavioural characteristics.

Two independent methods of quality assessment were used for this purpose; one using systematic assessment based on design specification, and the other using an expert-judged assessment technique. Due to the complicated nature of quality assessment, these two methods allowed detailed and triangulated analysis.

7.6.1 Quality Assessment Method One – Metric-based

The metric-based method of quality assessment is based on the specification, which states the requirements of a finished design. It is a relative measure, and can only give an indication of quality between a group of comparable designs.

The method itself forms a structured method of assessment designed to provide added benefit to the assessment of quality, with information regarding the areas in which a design is particularly strong and particularly weak built into the method. As the only purpose of its use within this work is for relative assessment and not for detailed analysis, its development is only summarised here, although it has been published previously (Snider et al., 2013b).

7.6.2 Metric-Based Method Development

The metric-based method is based on assessment through requirements of the design. Much literature addresses this need by developing criteria from the specification (see Garvin, 1987, Cross, 2000, Pugh, 1990, Ullman, 1997). Within this work, the "eight dimensions of quality" of Garvin (1987) are used:

Performance: a design outputs' primary operating characteristics.
Features: those characteristics that supplement basic functionality.
Reliability: the probability of malfunction or failure within a specified time period.
Conformance: the degree to which an outputs' design meets established standards.
Durability: the amount of use one gets from an output before it deteriorates.
Serviceability: the speed, courtesy, competence and ease of repair.
Aesthetics: How an output looks, feels, sounds, tastes or smells.
Perceived quality: Interpretation of the output through reputation.

Together, the dimensions of quality present a thorough description of all characteristics that contribute to the overall quality of a design output. In addition, as these characteristics can also define whether a product is of appropriate quality, the dimensions also allow interpretation of a product as creative to a certain extent (with further analysis required to classify originality and surprise).

However, in practice these categories may be of varying importance, depending on the particular design and its purpose. For example, the reliability of an artificial heart valve is far more critical than the importance of a mechanical pencil. To account for this variation in importance the Analytic Hierarchy Process (AHP) (Saaty, 1990, Vaidya and Kumar, 2006) was adopted. AHP uses an algorithmic method of calculating weights based, in this case, on the opinions of experts.

For this study a total of four experts were used with an average of 25 years engineering design experience (range 7 to 45). Each was asked to rank the importance of the dimensions of quality in this particular case, removing inaccuracy due to context. Their results were then collated according to the AHP method to produce appropriate weightings for each dimension.

The criteria within the specification could then be assessed for each design, and weighted appropriately. A simple better-same-worse method (Pugh, 1990) of assessment was used in this case, although many methods of specification evaluation would be suitable. Through appropriate summation of weights for each design, the metric-based method therefore allowed fair assessment of each design in relation to all others according to the categories that define design output quality.

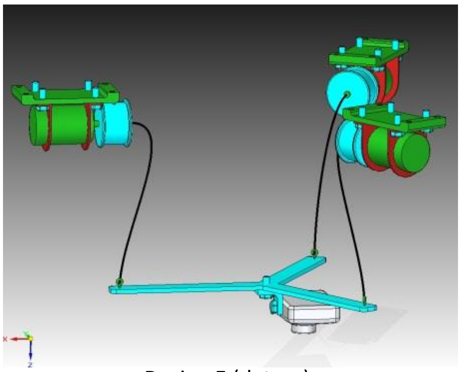
7.6.3 Metric-Based Method Assessment Process

All designs produced in study two were assessed using the metric method. To ensure accurate analysis, each was created in CAD software before assessment according to dimensions provided by the designer whenever possible, and to scale with sketches when not (see Figure 37). This allowed accurate measurement of relative size and approximate mass of each design, while the process of creating each model ensured a deeper understanding of the mechanisms and functions chosen by each designer.

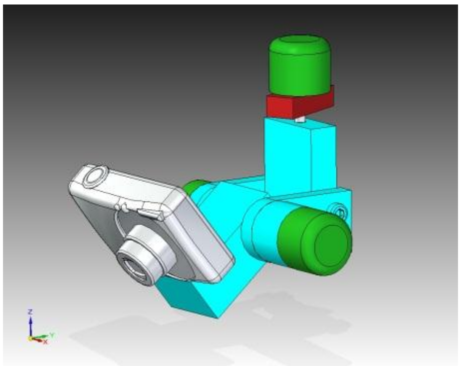
A datum design was chosen (that of designer 2E) as it was the most complete, and as such was widely comparable. Each design was then rated against it for all criteria within the specification. When a single design was not at sufficient completion to be assessed and the criteria could not be deduced from the model, none of the designs were assessed against it. This ensured fair analysis.

Following assessment, the scores for each design were weighted according to the results of the AHP to provide relative quality of each design.

As Design E formed a datum, scores in the metric-based method are based against it. As a result all scores for each design are relative, and are presented against a normalised scale where Design E scores 1.00, and all other designs score more or less against it. These scores above and below do not equate to percentage (i.e. A score of 1.20 for Design B would not imply a 20% improvement), but do demonstrate superiority. More detail of the assessment process of this study is provided in Snider et al. (2013b).



Design E (datum)



Design B

Figure 37: Example models used for assessment

7.6.4 Quality assessment Method Two – Judgement-Based

The second assessment method used the opinions of expert designers to determine quality of each design produced within study two. Five experts participated, with an average of 18 years engineering experience (range 7.5 to 29 years).

The assessment of a design as of quality is a subjective matter and likely in some manner reliant on the opinion of the assessor. For example, when specialist in manufacturing techniques, a designer may judge based the suitability of a design for manufacture with a lower priority on functional completion or performance.

As has been noted by others, however, the opinions of experts remain a valuable source of information. Amabile (1982b) notes the ability of experts to determine creativity of designs, while Potter and Levine Donnerstein (1999) advocate the use of experts to form a base for analysis in the use of some content analysis schemes to ensure validity. Due to the tacit knowledge that experts in a field possess, they are suitably capable to indicate better and worse solutions. In truth, due to their expertise, their opinions are more likely to be representative of the more subtle qualities of a design that are not considered in strict and rigid methods.

To minimise the effect of expertise in a specialism biasing results of the experts, several experts should be used. This has the effect of normalising results.

7.6.5 Judgement-Based Method Assessment Process

As the experts were to rate the quality of the design based on their personal views, no explicit development of a model was required. The method assessment still needs structure, however, which was provided through survey.

Using the complete 3D representation models produced for the metric-based method (as shown in Figure 37), each design was presented to the experts along with a very brief description of working principle, and a series of categories against which the experts were to judge. These categories concerned both quality of several abstract aspects of the design and design creativity, and were rated on a five-point Likert scale. The categories of assessment are shown in Table 41, and the survey sheets are presented in full in Appendix III.

Table 41: Survey table for expert judged quality

	1 - Bad	2	3	4	5 - Good
Function completion	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Concept	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Implementation	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Manufacture and assembly	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Overall quality	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Originality	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Appropriateness to the brief	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Value	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Creativity	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -

The categories of assessment were chosen for two reasons. The first was to provide indication of better and worse solutions; and the second to provide an indication of the consistency of each expert's opinions when assessing both creativity and quality. It is the former of these purposes that is presented in this work.

For the assessment of quality, the experts were asked to rate each design in terms of the functional completion of each design, the concept used, the way in which the concept was implemented, and the manufacturability and assembly. This allowed greater understanding of the properties that each expert thought were particularly strong. The additional category of overall quality was included for the experts to express their overall opinion.

For the assessment of creativity, the experts were asked to rate against terms used in the definition of creativity given by (Howard et al., 2008a), as well as creativity overall. This gave indication of the opinions of each expert, as well as interpretation of the traits that are particularly important for a design to be considered creative. The use of both "appropriateness" and "value" as terms of assessment was for the additional purpose of assessing correlation of terms used within the definition of creativity against the term creativity when judged alone; but does not form part of the reported results of this thesis.

Both creativity and quality can then be interpreted both from the overall scores given by the experts, and from the collation of their scores in each complementary category.

Assessment process

The process of expert assessment occurred over approximately 45 minutes. The experts were presented with all surveys sheets at once, and asked to carefully go through each without assessment. Their task at this point was to understand the working principles of each design. Each expert was then encouraged to ask any questions they had regarding how the designs worked and the assessment criteria. As the interpretation of the expert is the phenomena of interest in this case, experts were given little definition of categories, instead instructed to assess according to what they consider the category to represent.

The experts then assessed each design individually under the instruction that results should be relative to each design in the collection. They were not limited in time during this process.

Surveys were then collected, the scores collated and analysed. As data produced in this study was interval, all averaging or addition was performed using the median values. Results from this study are presented in tandem with results from studies one and two, in Chapters Eight and Nine.

7.7 Summary: Studies One and Two

The final parts of this chapter have presented two studies used for analysis of designer behaviour. These studied behaviour directly, through the use of a framework and coding scheme developed for purpose. These studies are different in nature but provide complementary results, as described in Section 7.5.

In addition to this direct analysis, analysis assessed the quality of designs produced in study two. By understanding which designs are considered better and which worse, both by a strict metric-based assessment and by assessment through expertise, some indication of better and worse behaviours to display can be gained.

Chapter 8: Results: The Appearance of Creative Behaviour

This chapter forms the first of those focused on presentation of results. Following introduction to the framework and coding scheme within Chapters Six and Seven, this chapter analyses the results relating to the appearance of creative behaviour within the design process in general, and within the later-stages of design specifically. In addition, it considers the impact of creative behaviour on output quality as judged by two separate methods. Results come from both studies one and two, and are analysed concurrently.

Results from this chapter are elaborated through consideration of design process of the designers in both studies one and two, as is presented in Chapter 7. Ten individual findings are presented, which are in turn discussed in Chapter 11 of this thesis.

8.1 Findings within this Thesis

Within the follow three chapters, twenty-six individual findings are presented directly following the results that evidence them within each study, and in tandem with brief discussion. Findings are then discussed in detail within Chapter 11.

As with the structure of the chapters themselves, findings can be described as belonging to differing categories (although not necessarily exclusive to any one). These categories represent the primary themes of research within the thesis as a whole. The final section within each chapter lists all findings and the categories to which they belong.

Creative Behaviour

The primary focus of the thesis is in creative behaviour in engineering, particularly at later-stages within the design process. A majority of the findings then concern creative behaviour specifically, or in combination with other categories.

Design Process

As with creative behaviour, the focus on later-stage engineering design places an importance of consideration of the entirety of the design process. This is firstly to understand design behaviour and creative behaviour in later-stage design, and secondly to place it in contrast to creative behaviour in early-stage design.

Design Behaviour

In addition to the study of creative behaviour, there is benefit in the more general study of patterns of behaviour as highlighted by the results, which do not relate to creative activity of designers. These findings contextualise the creative behaviour that does occur, by describing the typical process and behaviour within which it occurs.

Expert Behaviour

There are multiple benefits to the study of expert behaviour in design. First, by theoretical understanding, experts demonstrate behaviour that should lead to better results, and therefore represent better practice. Second, the study of industry designers working in a realistic setting present research of a higher contextual validity. Several of the findings presented here take advantage of these assumptions to provide further findings, as discussed within their relevant sections, and within Chapter 11.

8.1.1 Extending and confirming findings

In addition to these categories, findings within this work can be categorised as either an extension to current understanding within the field, or as confirmation of known findings or expectation within literature.

While the clear purpose of the thesis is in presentation of new knowledge to fill the knowledge gap identified in Chapter 4, there is also significant benefit in the confirmation of known or expected findings within literature. By demonstrating that the coding scheme generates results which are in keeping with current understanding of their subject, further validity is confirmed and confidence is gained.

The final section of each chapter lists which findings demonstrate new knowledge and which act as an extension, with discussion in Chapter 11.

8.2 Studies Summary

This chapter presents results from studies one and two, as presented in Chapter Seven, Table 42 provides a summary of these studies for clarity.

Table 42: Summary of studies one and two

	Study One	Study Two
Participants	7 undergraduate non-expert	10 undergraduate non-expert 4 industry expert (ave. 159 months) 2 industry non-expert (< 24 months)
Study type	Indirect observation Uncontrolled setting	Direct observation Controlled setting
Data	Logbook	Audio, video, screen capture, logbook, questionnaire
Brief	Varies dependent on participant	Identical for all participants
Length	22 weeks	4 hours
Team working	None	Some; unstudied

In total, 25 designers participated in studies one and two. In study one, seven undergraduates completed 22 week individual projects and were studied through their engineering logbooks; in study two, twelve experienced undergraduates, four experts, and two experienced but non-experts working in industry. This second study consisted of a design process in a setting that was familiar to each group of designers – university for the students and industry for the experts – and followed the methodology presented in Section 7.4.

Between the two studies, the participants completed 1238 individual tasks, of which 904 were applicable to the research. General task quantities are presented in Table 43 for context.

Where possible within this chapter, results from both studies are presented collectively or in direct comparison. Due to the different methodologies of each, certain comparisons are not possible, and are highlighted within the text. Other results however, particularly when discussing proportions of different types of task completed, are directly comparable. This direct comparison both informs the results, and produces independent findings in itself.

Table 43: General task numbers, Study one (whole process) and Study two (stage 3 only)

	Study One	Study Two	Overall
Total tasks	1045	193	1238
Proportion N/A (%)	32.0	0.00	27.0
Information type	364	32	396
Application type	347	161	508
Creative type	252	42	294
Non-creative type	459	151	610

8.3 The Appearance of Creative Behaviour

In both studies, designers completed both traditionally early-stage and late-stage tasks. This was a requirement of the projects that they were completing – in study one the designers completed both task analysis and conceptual design as part of the project, in study two the designers were required to perform task analysis and a conceptual design brainstorming session as part of the study procedure. Results concerning these design stages are presented in Chapter 9. Within this chapter, analysis occurs either over the whole design process, therefore concerning task analysis, concept design, embodiment design and detail design; or over what is termed later-stage design, referring to embodiment and detail stages only.

As measured by occurrence of expansion within tasks (see Section 6.4), designers completed varying quantities of tasks that over the whole process that evidenced creative behaviour, although with a reasonable standard deviation (see Table 44). As can be seen by the ratio of creative to non-creative tasks, some designers displayed significantly more creative behaviour than others. Particularly in study one (where the higher number of data points counteracts occurrence of anomalous results) a range of ratios from 0.300 to 0.813 (the proportion of creative to non-creative tasks; Table 44) demonstrates what might traditionally be termed variation in creative ability. In study two, a higher variation in creative ratio (range 0.333 to 1.80) also demonstrates this range of creative ability, although the greater extent of the range and standard deviation are likely a result of the lower number of data points and hence higher impact of extremes in the data. The difference in occurrence of creative behaviour between participants and majority of non-creative behaviour to creative is exemplified in

Table 44: Creative proportions for each designer (whole process)

Participant	Creative proportion (%)	Non-creative proportion (%)	Ratio (creative/non-creative)
1A	25.2	74.8	0.338
1B	44.8	55.2	0.813
1C	20.1	79.9	0.300
1D	25.0	75.0	0.333
1E	35.9	64.1	0.560
1F	38.4	61.6	0.622
1G	44.2	55.8	0.793
Average	**33.4**	**66.6**	**0.537**
S.D.	**9.20**	**9.20**	
2A	55.2	44.4	1.25
2B	28.6	71.4	0.400
2C	45.0	55.0	0.818
2D	33.3	66.7	0.500
2E	37.0	63.0	0.588
2F	39.1	60.9	0.643
2G	56.3	43.8	1.29
2H	50.0	50.0	1.00
2I	38.9	61.1	0.636
2J	25.0	75.0	0.333
2K	64.3	35.7	1.80
2L	46.2	53.8	0.857
Average	**43.2**	**56.7**	**0.843**
S.D.	**11.3**	**11.3**	

Due to the inherently subjective and variant nature of creativity, precise proportions cannot be expected to consistently reflect real life. On average however, designers displayed creative behaviour in significantly lower proportion to non-creative behaviour at an approximate real-life proportion of one third creative, to two-thirds non-creative ($p \leq 0.0001$; Wilcoxon signed rank test).

Two findings can be presented from this data, discussed in Section 11.4:

One: *Within the design process as a whole, creative behaviour is in a minority to non-creative behaviour.*

Two: *Different designers will display varying quantities and forms of creative behaviour, whether completing different projects (as in study one) or the same (as in study two).*

Further detail of creative behaviour in relation to individual design stage is presented in Chapter 9.

8.4 Creative Approach in Later-Stage Design

Focusing specifically on later-stage design, a primary finding of this work concerns designer creative style or, as termed within this work and in relation to task sequence, designer creative *approach*.

This is determined through relative proportion of expansive information-type and application-type tasks (therefore *astute-* and *effectuating-type* tasks) completed by the designers (see Section 6.3). Presented here the results concern only later-stage design.

Table 45 shows proportions of information and application type tasks completed by each designer, as well as the proportion of each that demonstrated creative behaviour. Particularly clear amongst these results is the tendency for designers to fall into two primary groups of creative approach, those who more often complete *astute-type* tasks (termed as following an *astute* approach) and those who more often complete *effectuating-type* tasks (termed as following an *effectuating* approach).

Primary approach is here assigned as the type by which the majority of the participants' tasks occurred, as defined by output. These descriptors are provided for the sake of clarification and understanding, numerical results are used in all analysis.

As shown in Table 46, the average difference between proportion of astute and effectuating tasks is large, as is the standard deviation; in general, there is a significant majority of one creative task type over the other.

That two different approaches to completing creative behaviour are evident in later-stage design is an important finding, as will be discussed in Chapter 11. Relating to such aspects as problem solving strategy, designers display dramatically different behaviours in later stage design, even though the fundamental activities of the stages are very similar. This raises questions regarding appropriateness of different approaches in later stages, effectiveness of different approaches, and methods of designer support throughout the design process.

Particularly interesting within Table 45 is the fact that different creative approaches are evident in designers from both studies. In study one, designers completed different projects (though all involved physical design); in study two, all designers completed exactly the same project, with exactly the same resources available to them. Even within groups (as were present during the second study at certain points, see Section 7.4) designers did not all display identical approaches, with both a two to one split of effectuating approaches to astute approaches (designers 2A, 2B and 2C, for example) and a two to one split of astute to effectuating approaches (designers 2G, 2H and 2I).

This finding demonstrates that creative approach is primarily a designer-related trait, rather than primarily a project-related trait. Even when completing an identical brief the primary approach followed can vary, and as such is a factor dependent on designer and design situation, rather than project. Thus these data demonstrate the finding that:

Three: *Different designers will display different creative approaches within later stages of the design process, even when completing identical projects.*

This is not to say that an approach followed by any designer is constant and unchanging, as will be shown in Chapter 8, but does demonstrate the presence of multiple forms of behaviour, independent of the activity and project under way.

Primary approach is here assigned as the type by which the majority of the participants' tasks occurred, as defined by output. This are provided for the sake of clarification and understanding, numerical results are used in all analysis.

Table 45: Creative proportions of information and application type tasks, and corresponding creative approach (later-stage only)

Study 1					
Designer	**Information Focus (%)**		**Application Focus (%)**		**Primary approach**
		Expansive Proportion (astute) (%)		Expansive Proportion (effectuating) (%)	
1A	45.2	24.2	54.8	17.5	Astute
1B	48.8	25.0	51.2	47.6	Effectuating
1C	30.0	26.7	70.0	20.0	Astute
1D	15.4	0.00	84.6	18.2	Effectuating
1E	32.1	40.7	67.9	26.3	Astute
1F	42.9	14.6	57.1	45.3	Effectuating
1G	43.0	23.5	57.0	46.7	Effectuating
Average	**36.8**	**22.1**	**63.2**	**31.7**	
Study 2					
2A	25.0	0.00	75.0	50.0	Effectuating
2B	5.56	0.00	94.4	23.5	Effectuating
2C	16.7	50.0	83.3	40.0	Astute
2D	44.4	25.0	55.6	40.0	Effectuating
2E	11.1	0.00	88.9	18.8	Effectuating
2F	45.5	40.0	54.5	16.7	Astute
2G	16.7	100	83.3	20.0	Astute
2H	42.9	33.3	57.1	25.0	Astute
2I	33.3	0.00	66.7	16.7	Effectuating
2J	0.00	0.00	100	0.00	Standard
2K	40.0	0.00	60.0	0.00	Standard
2L	33.3	0.00	66.7	0.00	Standard
2M	33.3	0.00	66.7	25.0	Effectuating
2N	5.60	100	94.4	41.2	Astute
2O	0.00	0.00	100	20.0	Effectuating
2P	15.4	0.00	84.6	36.4	Effectuating
2Q	0.00	0.00	100	8.30	Effectuating
2R	0.00	0.00	100	0.00	Standard
Average	**20.5**	**19.4**	**79.5**	**21.2**	

Table 46: Average difference in creative task occurrence (i.e. difference between proportion of one creative approach and the other) (later-stage only).

	Average difference in expansive task occurrence	S.D.
Study 1	17.5	16.8
Study 2	21.9	30.5

8.4.1 Correlation against Creative Style Measures

Stating the terms creative approach and creative style infer potential relation between creative approaches as identified within these data and creative styles as described in psychological literature. To attempt to identify such relation, each designer taking part in studies one and two also completed a creative style test, similar to the Kirton Adaption-Innovation (KAI) scale (Kirton, 1976) (see Table 47). These data were then assessed for correlation using Spearman's rank sum correlation, and assessed for significance using a two-tailed t-test.

It should be noted that the Spearman rank correlation coefficient is used for each of these correlations. As such, the correlation states that a relationship exists between the variables, but does not infer linearity. Due to the complex nature of creativity and the study of human behaviour, there is little basis to assume that strength of creative approach is linearly related to any of the measured variables of the coding scheme. Similarly, it is not the purpose of the coding scheme to produce predictive understanding of the relationships between variables, only to identify trends between. Correlation therefore states that a relationship between variables does exist and is significant, but does not infer the pattern that the relationship follows. As such the Spearman rank sum method is more suitable than the Pearson method, which does infer linearity in relationship. Results from correlation analysis are shown in Table 48.

The creative behaviour test scores have a mean of 101, with a slightly lower standard deviation than found by Kirton in his original work (11.7 in these studies rather than 17.5; Kirton (1976)). As the domain of engineering requires lower rigidity in order to allow solutions to be found, and so is of a form in which a higher mean is to be expected (Kirton and Fender, 1982), and the population in this study is all of similar background, these values are in line with expectation.

As introduced within Section 2.3, the KAI scale ranks designers on a spectrum from *adaptor* to *innovator*, each based on personality and claiming fundamentally different personal traits. Although contested by Kirton to be independent of creative level, others have found significant relationships between the KAI scale and a number of creative level tests (Isaksen and Puccio, 1988). This analysis takes a similar view – a person who scores highly on the KAI scale (and is therefore classed as an *innovator*) is also one who is seen as typically more creative. Within the scope of studies one and two, it is then expected that a higher KAI score should correlate with a high demonstration of creative behaviour by the designer. This interpretation is further discussed in Section 11.4.

Additionally, the KAI scale highlights two different styles of creativity. The first advocates creativity through "doing things better" (*adaption*), in which a designer will work hard within well-understood paradigms to overcome problems and achieve highly-appropriate results. The second advocates creativity through "doing things differently" (*innovation*), breaking existing paradigms and forming new solutions principles through more "chaotic" exploration and development. While the relationship between the definition of these styles as creative and the definition of creative approach within this work has not yet been clarified (see Section 11.4), correlation of the creative approaches as identified by this work and creative style as defined by the KAI scale would provide both validation and understanding of the coding scheme.

Table 47: Creative style test scores (later stage)

Participant	Primary creative approach	Ratio creative/non-creative	Creative style test score
1A	Astute	0.259	89
1B	Effectuating	0.577	95
1C	Astute	0.282	97
1D	Effectuating	0.182	74
1E	Astute	0.448	105
1F	Effectuating	0.474	113
1G	Effectuating	0.580	110
2A	Effectuating	0.600	100
2B	Effectuating	0.286	104
2C	Astute	0.714	100
2D	Effectuating	0.500	116
2E	Effectuating	0.200	99
2F	Astute	0.375	98
2G	Astute	0.500	117
2H	Astute	0.400	128
2I	Effectuating	0.125	110
2J	Standard	0.00	97
2K	Standard	0.00	81
2L	Standard	0.00	91
2M	Effectuating	0.200	106
2N	Astute	0.800	103
2O	Effectuating	0.250	96
2P	Effectuating	0.444	112
2Q	Effectuating	0.0910	85
2R	Standard	0.00	102
Average		**0.331**	**101**

Table 48 shows correlations of the data with the creative style test, for both study one and study two. In each case, the creative style test shows significant correlation with the occurrence of late-stage expansion, a defining feature of creative behaviour.

As the innovator within the KAI scale is thought to be the more creative by traditional understanding, the correlation with late-stage expansion acts as one form of confirmation of validity of the coding scheme. The KAI scale is a fully external measure, and as such that it and expansion as measured by the coding scheme are significantly related demonstrates the ability of the coding scheme to identify creative behaviour. Particularly in relation to the difference in creative approaches stated by the KAI test as a measure of creative style, the relationship between correlations and interpretation is further discussion in Section 11.4. At this point in the work it is then sufficient to state a single finding of scheme validity, which shall be explored fully at a further point:

Four: *Creative behaviour within later design stages correlates significantly with creative style.*

Table 48: Correlations between creative style test and study variables (later-stage)

First variable	Second variable	Correlation (ρ=…)	Significance (p=…)
Study 1			
Creative style test	Late-stage expansion	0.714	0.0357
Study 2			
Creative style test	Late-stage expansion	0.534	0.0224
Combined			
Creative style test	Late-stage expansion	0.485	0.0141

Correlation has been calculated by a Spearman rank correlation, and significance demonstrated by a two-tailed students t-test. All correlations would typically be interpreted as medium strength and positive.

8.5 Typical Creativity in Later-Stage Design

Separate to concepts of individual difference and creative approach, studies one and two provide findings related to "typical" creative behaviour; patterns that all designers display. As with the main focus of the thesis, the findings presented here concern the later stages of the design process.

As seen in Table 49, within later-stage design and for the moment ignoring any individual difference, similar proportions of astute tasks and effectuating tasks were completed (20.1% and 24.1% respectively). Although the standard deviation of astute task occurrence in Table 49 is near twice that of effectuating, this is a result of performing analysis on a smaller number of information-type tasks in study two, rather than a trend within the data. When the standard deviations are taken of both astute and effectuating task occurrence for only study one, both lie within the range of 11-13%. Thus the data shows that, although the designers are split between those who follow an astute approach and those who follow an effectuating approach, neither group characteristically displays more frequent creative behaviour than the other.

One further finding that can be taken from general results is similar to finding one; expansive tasks are in the minority during the design process. Difference exists, however, in the smaller proportion of expansive tasks to restrained tasks. Whereas over the whole process the ratio is approximately 1:2 (expansive : restrained), in later stages this leaps to 2:7 (22.6% expansive: 77.4% restrained; Table 49). Later stage design can therefore be described as being completed in a less creative manner than early ($p \leq 0.0002$; Wilcoxon signed rank test):

Five: *Later-stage design typically contains less creative behaviour than early-stage design.*

This finding can be clearly seen in Figure 38, which shows the early and late stage creative proportions for each designer for whom the data was available.

Table 49: Expansive task proportions in later stage design (Studies one and two combined)

Task type	Designer Average (%)	Standard Deviation (%)
Expansive	22.6	13.4
Restrained	77.4	13.4
Effectuating	24.1	15.5
Astute	20.1	28.3

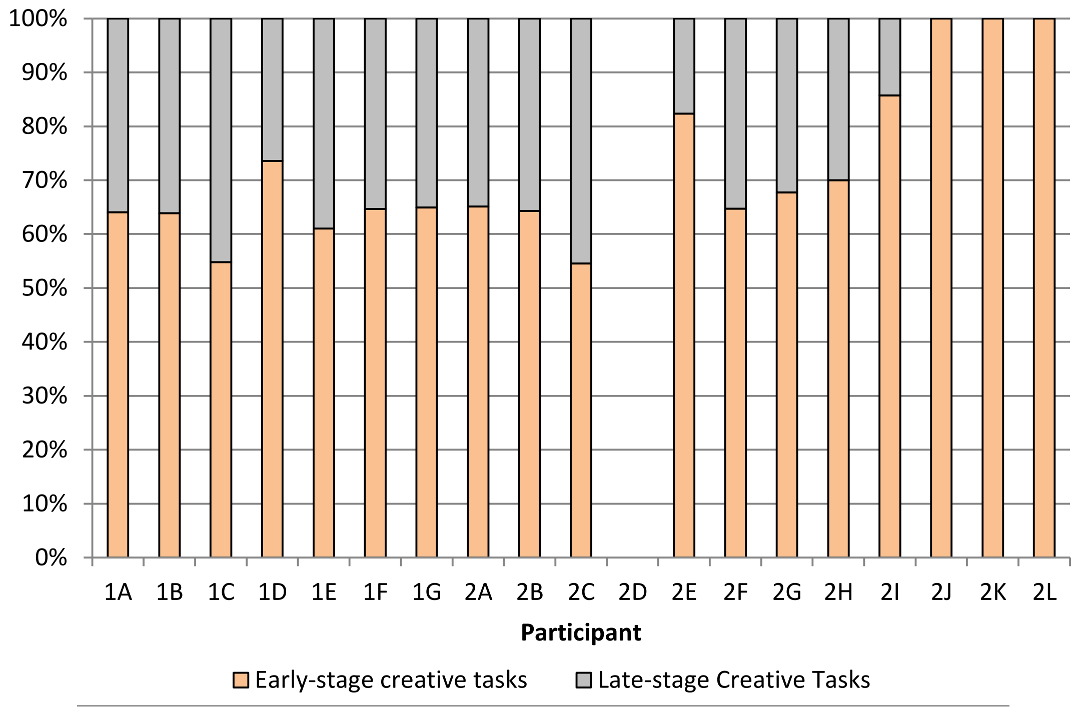


Figure 38: Proportion of creative behaviour by design stage

N.B. *Due to issues with early-stage data, Figure 38 contains no data for designer 2D.*

8.5.1 Patterns in Creative Task Types

In Section 6.3, tasks were described as either within-entity (when the input entity was of the same type as the output), or as cross-entity (when the input and output entities were of different types). The proportions of occurrence of these task types are shown in Table 50.

It is striking that throughout both studies one and two, only one designer (1D) completed a majority of within-entity tasks expansively while 19 designers demonstrated a majority of cross-entity expansion. This clear example demonstrates a preference for a higher proportion of cross-entity tasks to be completed creatively ($p \leq 0.0001$; Wilcoxon signed rank test), and thus a clear trend in creative behaviour. Discussed in Section 11.4, this is a clear finding that:

Six: *Designers more frequently display creative behaviour when completing cross-entity tasks.*

It is particularly interesting that this trend exists regardless of project, (as demonstrated by the same pattern appearing in both studies one and two) and so is more likely a result of the designer than the project itself.

Additionally, Table 50 shows a difference in proportions of within-entity tasks and cross-entity tasks between studies one and two. In the former, designers completed very similar proportions for each (47.8% within entity, 52.2% cross-entity). In study two, within-entity tasks were far more common (66.6% within-entity, 33.3% cross-entity). This could be a result of the methodological situation of study two; when limited heavily by time, it is perhaps likely that designers will focus their working practice to achieve as high a level of completion as possible. There is an argument to be made that the higher proportion of within-entity tasks is a result of this streamlining, either as an active attempt to reduce creative behaviour (which may involve exploration, and hence increase time commitment to a task), or with a reduction in creative behaviour as a consequence. This is further discussed in Section 11.5, but presents the finding that:

***Seven:** The proportion of within-entity tasks to cross-entity tasks is in part indicative of the design situation and process streamlining.*

Table 50: Creative proportions of within-entity and cross-entity tasks; later stage design (studies one and two)

Study 1					
Designer	**Within-Entity Tasks (%)**		**Cross-Entity Tasks (%)**		**Primary approach**
		Expansive Proportion (%)		Expansive Proportion (%)	
1A	39.7	13.8	60.3	25.0	Cross-Entity
1B	31.7	26.9	68.3	41.1	Cross-Entity
1C	46.0	8.70	54.0	33.3	Cross-Entity
1D	74.4	17.2	25.6	10.0	Within-Entity
1E	63.1	18.9	36.9	51.6	Cross-Entity
1F	39.3	22.7	60.7	38.2	Cross-Entity
1G	40.5	31.3	59.5	40.4	Cross-Entity
Average	**47.8**	**19.9**	**52.2**	**34.2**	
Study 2					
2A	37.5	33.3	62.5	40.0	Cross entity
2B	72.2	15.4	27.8	40.0	Cross entity
2C	66.7	25.0	33.3	75.0	Cross entity
2D	66.7	33.3	33.3	33.3	None
2E	50.0	11.1	50.0	22.2	Cross entity
2F	63.6	14.3	36.4	50.0	Cross entity
2G	66.7	25.0	33.3	50.0	Cross entity
2H	71.4	20.0	28.6	50.0	Cross entity
2I	44.4	0.00	55.6	20.0	Cross entity
2J	90.0	0.00	10.0	0.00	None
2K	60.0	0.00	40.0	0.00	None
2L	83.3	0.00	16.7	0.00	None
2M	66.7	0.00	33.3	50.0	Cross entity
2N	66.7	33.3	33.3	66.7	Cross entity
2O	70.0	0.00	30.0	66.7	Cross entity
2P	69.2	22.2	30.8	50.0	Cross entity
2Q	66.7	0.00	33.3	25.0	Cross entity
2R	86.7	0.00	13.3	0.00	None
Average	**66.6**	**12.9**	**33.4**	**35.5**	

8.6 Creative Level and Other Results

In addition to the creative behaviour test, 12 participants of study two also completed the Torrance Tests of Creative Thinking (TTCT) Figural Form A (Torrance, 2008). As described in Section 2.3, these tests are designed to determine creative level of a person, and hence inherent creative ability. Results are shown in Table 51.

The TTCT test results were then correlated against the data produced by the coding scheme, with interesting correlations shown in Table 52.

Table 51: Torrance Tests of Creative Thinking (TTCT) scores

Participant	Creative Style Test	Torrance Score	Torrance Index
2A	100	96	104
2B	104	108	119
2C	100	113	125
2D	116	103	114
2E	99	124	143
2F	98	125	144
2G	117	108	124
2I	110	96	110
2J	97	105	117
2K	81	100	110
2L	91	99	112
2M	106	103	119

N.B. *Participant 2H was omitted from analysis due to incorrectly completing the test.*

Before analysis of these correlations, it is important to put the purpose of the TTCT in context with the measured results of the studies and the KAI scale. The TTCT tests are designed to measure five distinct characteristics of the personality of a person, which should by theory enable a person to produce a highly creative result. It is therefore tied closely to personality traits of a designer, and the actual result.

However, the TTCT does not by any measure analyse the actual working process of a person – only interpretive features one might expect to see within it. For example, a measure of fluency within the TTCT (measured by quantity of ideas that a designer can produce) requires exploration in a single case – i.e. production of as many ideas as possible that meet certain criteria. In terms of creative behaviour as measured by the coding scheme, this would account for a single act of expansion – while the TTCT states that a higher quantity of ideas demonstrates higher creativity, the coding scheme is only concerned with the fact that a process of multiple solution generation occurred. Further, a measure of originality within the TTCT (measured by abstract completion of test procedure) also required expansion in design behaviour. However, this category also falls to the same limitation as fluency above – the coding scheme does not distinguish between extent of originality in different tasks – as well as the fact that by the coding scheme a designer can display creative behaviour without distinct originality (i.e. exploration does not require the designer to choose the most original solution found). It is held that it is equally valid to explore varying, unoriginal concepts to identify a solution, which may then be interpreted as creative either through unusual combination of concepts into a solution (which would by the TTCT account for only a single case of originality); or through exceptional performance and appropriateness to the brief.

Each of these cases demonstrates a difference between interpretation of creative level of a person and the creative behaviour that they display. As held by the coding scheme, a designer is creative through their actions within a task as they expand upon possible solutions and identify viable opportunities. As held by the TTCT test, a designer is of higher creative level through personal characteristics that can be interpreted from their work. Although from these characteristics it is possible to infer some features that will appear in a creative designers' process, the TTCT lays no claims on the quantity of occurrence of these characteristics within the extent of a designer's process, or indeed of the actual process of a designer and the creative behaviour displayed within.

This difference between TTCT and the coding scheme is not seen as positive or negative, but rather as indicative of their different purposes. The TTCT as a measure of creative level; the coding scheme as an analysis method of creative process. As a result, there is little expectation of correlation between study variables and the TTCT test. Although the TTCT should identify the more creative of the designers, this relates less to the quantity of expansive tasks that they completed and their actual creative behaviour, and more to the quality of their creative behaviour through the traits that the designer displays. This form of analysis is not the current purpose of the coding scheme, and is not considered within this thesis.

Such a discrepancy between creative level and creative behaviour within the TTCT also underlines the suitability of the KAI scale within this work. Although there is some contention to whether KAI measures creative style or level (see Section 2.3), it does base its analysis on expected actual process behaviour of a designer based on personality, and hence is much closer in focus to the coding scheme developed within this work.

Table 52: Correlations involving TTCT results

First Variable	Second Variable	Correlation (ρ=...)	Significance (p=...)
TTCT score	Effectuating task proportion	0.0690	0.831
	Astute task proportion	0.498	0.0994
	Late-stage expansion	0.315	0.313

Within correlation analysis against the TTCT test, there is a single correlation against the proportion of tasks completed in an astute manner in later-stage design, all other tested correlations were non-significant. As such, the TTCT would state that the more astute designers in late-stage design are those of higher personal creative level. As expected, no correlation exists between expansion and the TTCT, in line with previous discussion.

These results therefore suggest that the creative level of a designer as assigned by the TTCT is linked to their ability to be creative in information-type tasks in later-stage design. When compared with several findings yet to be presented, this is an interesting finding. At this point, it forms the formal statement that:

Eight: *Creative level is related to the proportion of tasks completed in an astute manner.*

8.7 Creative Behaviour and Output Evaluation

As all designers within study two completed the same project brief and produced, to a comparable level, designs of the same level of completion and detail, they can also be compared in relation to their quality. This was not possible for study one, as the designers completed different projects.

To provide further understanding of the processes followed by designers, particularly in relation to the characteristics of their results, each design in study two was evaluated according to two methods. First, quality assessment was completed using a metric-based method, developed and presented in other work (Snider et al., 2013b). Second, each design was rated using a Consensual Assessment Technique (CAT) (Amabile, 1982b) for both design quality and design creativity. The methodology for these assessments is presented in Section 7.6.

8.7.1 Metric-Judged Quality Assessment

The metric-method uses a systematic method of categorisation and assessment based on specification points, using the better-same-worse method of assessment (Pugh, 1990). Further, it uses an Analytic Hierarchy Process (AHP) (Saaty, 1990, Vaidya and Kumar, 2006) to form weightings for each category, ensuring fair analysis based on design context.

The metric method described design quality at multiple levels, which may or may not be of relevance depending on project and design situation. In this case, the designs were rated at the internal direct quality level – which considers the performance of the design itself – and at the overall level, which includes the same but also factors in specifications relating to manufacture, assembly and super-system performance. The distinction between these categories has little impact on analysis within this work, but demonstrates validity in correlation between the metric-based and expert-judged assessments methods (see Table 53 and Figure 39). For a detailed description, see Snider et al. (2013b). Note that in Figure 39, relative height between the metric and expert judged methods is due to methodology, and is not representative of quality.

Table 53: Quality of produced designs (Study two)

Participant	Metric-Judged Quality		Expert-Judged Quality
	Internal direct quality	Overall quality	
2A	0.819	0.485	4
2B	3.10	1.57	4
2C	0.594	0.339	3.5
2D	2.84	1.79	3.5
2E	5.76	1.48	3
2F	1.00	1.00	3
2G	2.72	1.43	3.5
2H	1.00	0.554	3
2I	2.23	1.02	3
2J	2.26	1.30	3.5
2K	1.90	1.08	2
2L	1.28	0.636	3
2M	3.71	1.21	3
2N	4.84	2.16	3.5
2P	0.779	0.432	4
2Q	4.59	2.24	4
2R	3.18	1.60	3

Under correlation analysis, the metric method produced significant correlation only with the total number of tasks completed by each designer ($\rho=0.538$, $p=0.0213$). This would suggest that designers who are capable of completing a higher number of tasks in the methodological situation of study two are also those who will produce better results. As study two was limited in terms of time and designed to demand a high rate of working from the participants, this perhaps relates to more efficient working, decision making skills, or solution strategy. No other significant correlations were found against quality, indicating that approach and other behavioural characteristics are not highly influencing factors. This is further discussed in Section 11.5, and suggests the finding that:

Nine: *In a time-dependent situation, design quality is related to a higher number of discrete tasks completed by a designer.*

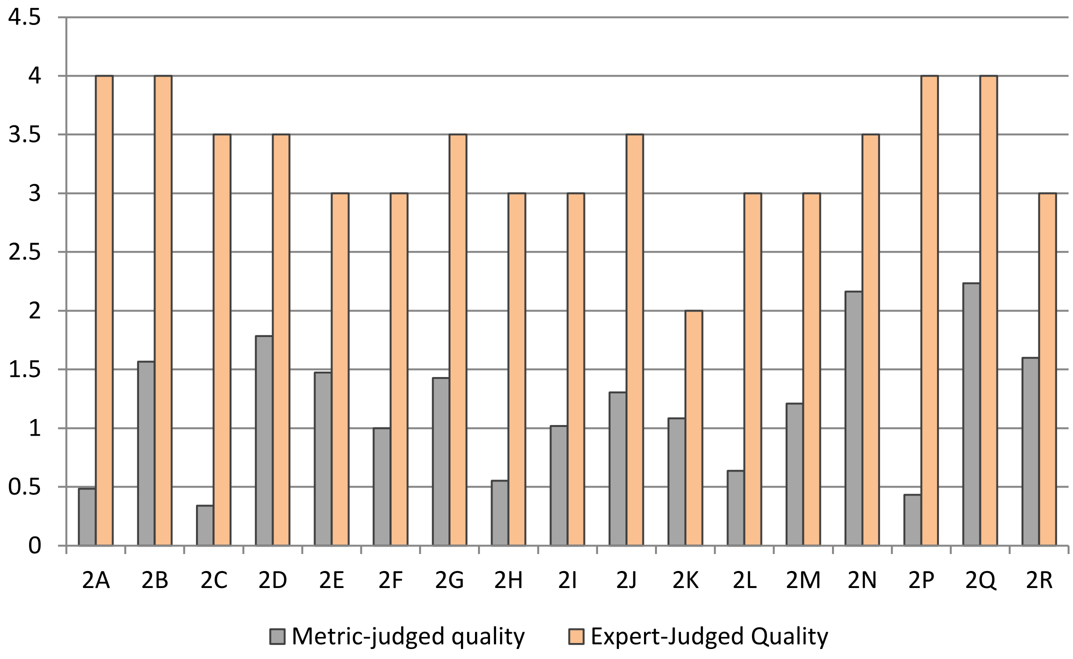


Figure 39: Metric and expert quality of produced design

No correlation was found between metric-judged quality and any creative behaviour related variable. Although unfortunate, this is not a surprising result. The coding scheme itself is not designed to determine quality of a solution, or even to identify which solutions are of a higher creative level at completion. The occurrence of creative behaviour within a design process may be a necessity for highly creative solutions to be developed, but there is no guarantee that a creative output will be produced. Creative behaviour cannot be said to imply quality, only to create the conditions by which high quality may occur.

8.7.2 Expert-Judged Assessment

The case of purely Expert-Judged assessment plays a slightly different role. As demonstrated by others, Consensual Assessment Techniques (CATs) (of which this expert-judged assessment is one form), are reliable, in that judges will consistently select the same designs for each category that they are asked to rate (Amabile, 1982b). It is then to the researcher to ensure that the categories against which the experts rate are reflective of what they are attempting to classify.

For this analysis, experts were asked to rate based on several categories using a five-point Likert scale (see Appendix III), designed to identify both those designs judged as of quality and those judged as of high creativity. Results can then be collated, and the median values used for analysis.

Creativity as a human-interpreted concept is in truth closely associated with quality, as evidenced by the use of quality or similar terms in the creativity definition (within this work, *appropriateness* is used). As a result, it is unlikely that creativity and quality can be entirely decoupled within the minds of the experts during their assessment, as is possible when assessing quality through the metric method.

However, considering the focus of this work on later-stage design, the assessment of both quality and creativity by the expert judges is useful. As has been demonstrated, creativity is commonly associated with earlier stages of the design process, and hence with creativity in terms of functional completion and solution principle rather than detailed behaviour and system structure. For this reason, assessment of creativity by experts may not highlight those designs for which the designer was highly creative in later-stage design – such behaviour is less likely to produce radical originality as the designer is working primarily on more detailed elements such as system structure and system behaviour. As a result, there is no guarantee of correlation between expert assessment of creativity and later-stage occurrence of creative behaviour.

The context-independent nature of the metric method is a weakness that is not present in expert judgement of quality. Through their expertise, such judges are able to consider the design situation and circumstance of any design problem, and produce an appropriate rating. While this assessment may not consider all specifications and requirements to the same level of detail as the metric method, assuming the combined opinions of the experts are in combination somewhat accurate due to their expertise, it will produce an accurate result.

Table 54: Correlates of quality in later stage design (Study two)

First Variable	Second Variable	Correlation (ρ=...)	Significance (p=...)
Expert-judged quality	Later-stage expansion	0.479	0.0517
	Application-type tasks	0.510	0.0509
	Effectuating task proportion	0.495	0.0434

Correlation analysis was conducted on this data, as shown in Table 54. Against the Expert-Judged quality method, correlation exists against later-stage expansive task occurrence, an overall majority of application-type tasks, and a higher proportion of effectuating-type tasks, although the latter two of these are of borderline significance. No other significant correlations were found relating expert-judged quality to behavioural traits as identified by the scheme, indicating that those categories in Table 54 are the only ones of importance, as identifiable by the scheme. As such, the data demonstrates that those designers who exhibit a higher proportion of creative behaviour in later-stage design will also produce better results when judged by another, and that the same conclusion can be made for a focus on application-type tasks, giving the finding that:

Ten: *Design quality, as judged by experts, is related to a focus on application type tasks, and a higher frequency of occurrence of creative behaviour.*

8.7.3 Comparison of Metric and Expert Judgement

Although correlation between study variables and quality assessment was only present for the expert-judged method, it is to be expected that both methods should correlate when compared directly. These correlations are shown in Table 55, and show a significant relationship in each case. As each method is designed to identify quality, and correlation exists between the two, it is a fair assumption that both are to some extent accurate.

Table 55: Correlates between metric and expert based quality assessment methods

First Variable	Second Variable	Correlation (ρ=...)	Significance (p=...)
Expert-judged quality	Metric-judged overall quality	0.522	0.0316
	Metric-judged internal quality	0.487	0.0474

That only one method of assessment correlates significantly with the study variables demonstrates that some care must be taken in interpretation, and that the study variables are not the sole contributors to solution quality. This is to be expected given the nature of design; the quality of a solution is a culmination of the process followed by the designer, the brief they are given, and the resources they choose to utilise, amongst other variables. Correlation therefore provides insight, but does not provide complete understanding.

8.8 Summary: The Appearance of Creative Behaviour

This chapter has presented findings concerned with creative behaviour within the later stage design process, and the appearance of creative approaches by individual designers. These findings are listed in Table 56, and are discussed in Chapter 11. Note that the second column indicates whether the finding represents new knowledge, or confirmation of current or expected knowledge within the field.

This section concludes the presentation of results relating to the appearance of creative behaviour and creative approach alone. Chapter 9 elaborates on the findings here presented through consideration of design stage and design process within both studies.

Table 56: Summary of findings on the theme of the appearance of creative behaviour

Finding Number	New finding/ confirming finding	Finding
1	Confirming	*Within the design process as a whole, creative behaviour is in a minority to non-creative behaviour.*
2	Confirming	*Different designers will display varying quantities and forms of creative behaviour, whether completing different projects (as in study one) or the same (as in study two).*
3	New	*Different designers will display different creative approaches within later stages of the design process, even when completing identical projects.*
4	New	*Creative behaviour within later design stages correlates significantly with creative style.*
5	Confirming	*Later-stage design typically contains less creative behaviour than early-stage design.*
6	New	*Designers more frequently display creative behaviour when completing cross-entity type tasks.*
7	New	*The proportion of within-entity tasks to cross-entity tasks is in part indicative of the design situation and process streamlining.*
8	New	*Creative level is related to the proportion of tasks completed in an astute manner.*
9	New	*In a time-dependent situation, design quality is related to the number of discrete tasks completed by a designer.*
10	New	*By expert judgement, design quality is related to a focus on application type tasks, and a higher frequency of occurrence of creative behaviour.*

Chapter 9: Results: Creative Design Process Behaviour

An advantage of the coding scheme used within this work is its identification of tasks as occurring at different design stages, where stages are defined according to their focus on development of function, development of system behaviour, or development of structure. As a result it is possible to analyse the behaviour of designers in context of the stage of design at which they were working, to identify stage-specific patterns of creative and non-creative behaviour.

It is to this purpose that this chapter has been aimed, presenting findings from studies one, two, and three, with relation to design stage, progress through stages, quality, and the relation of all of these to the appearance of creative behaviour.

This chapter also forms the conclusion of the presentation of primary findings relating to designer behaviour within the engineering design process.

9.1 Studies Summary

This chapter presents results from studies one and two, as presented in Chapter Seven, Table 57 provides a summary of these studies for clarity. Experience of the participants is given in brackets in the respective sections of the table.

Table 57: Summary of studies one and two

	Study One	Study Two
Participants	7 undergraduate non-expert	10 undergraduate non-expert 4 industry expert (ave. 159 months) 2 industry non-expert (< 24 months)
Study type	Indirect observation Uncontrolled setting	Direct observation Controlled setting
Data	Logbook	Audio, video, screen capture, logbook, questionnaire
Brief	Varies between participants, all briefs were individual	Identical for all participants
Length	22 weeks	4 hours
Team working	None	Some; unstudied

9.2 Stages of the Design Process

By way of reminder, the stages of the design process in this work are defined in terms of their focus. This is in contrast to other methods of interpretation, which rely on chronology of occurrence of certain activities to define design stage (Pahl and Beitz, 1984), or on level of system hierarchy to determine level of detail (Suh, 1990).

Definition by focus in this way allows the assertion that the classical design process can occur at multiple levels of detail and many points in time. For example, there may be need to perform typical concept design on the transmission system, the gearbox, and the individual gears within, all of which reside at different levels of detail and would be completed at different points in time. Table 58 gives the definitions of design stages used within this work. These definitions mirror those presented in Chapter 3.

Table 58: Definitions of design stages

Design Stage	Definition
Analysis	Determine the desired and required functions of the system, for it to complete its purpose.
Concept	Conceive the system functions in detail through preliminary description of system behaviour.
Embodiment	Design detailed system behaviour through preliminary description of system structure.
Detail	Design and finalise system structure, and all aspects that may influence it.

9.3 Design Process Progression

As discussed in Section 3.4, the situation in which designers are working changes significantly as the process continues. In addition to an increase in constraint (McGinnis and Ullman, 1990, Howard et al., 2011) and in activity focus (Pahl and Beitz, 1984, Pugh, 1990), the type of tasks that designers complete varies through the design process.

When working within early-stages, designers have a significant focus on information based tasks (82.9% information, study one, Table 59; 90.9% information, study two, Table 60; $p \leq 0.0001$, Wilcoxon signed rank test). As design continues, this shifts to a slight focus on application based tasks in both embodiment and detail stages.

Thus the data demonstrates that, as discussed in Section 11.3:

Eleven – *Through the stages of design, there is a general shift in focus from information-type tasks to application-type tasks*.

Table 59: Task focus in design stages, average across all participants (Study one)

Design Stage	Task type (%)	
	Information	Application
Analysis and Concept (early stage)	82.9	17.1
Embodiment	38.9	61.1
Detail	36.6	63.4

Table 60: Task focus in design stages, average across all participants (Study two)

Design Stage	Task type (%)	
	Information	Application
Early Stage	90.9	9.10
Late Stage	20.9	79.1

Due to the structure of study two (with a specific early-stage design segment and specific later-stage design segment) and the time limit present, separation between embodiment and detail design within these stages does not create sufficient granularity for analysis. As the focus of this work describes later-stage design as both of these stages as a whole, this is a suitable condition for analysis. However, as a result, any description of embodiment design as separate to detail design within this section includes only study one. It is for this reason that Table 60 contains categories only for "early stage" and "late stage" design.

It is also interesting that study two presents a higher difference in focus between design stages than study one. This could be a result of the structure of the study. The limited time available for design during study two created a significant constraint that was not directly present during study one, and hence designers may have intentionally streamlined their process to increase the level of completion that they may reach. Should this be the case, the stronger bias for one task-type over the other in study two may be a result of process streamlining.

9.4 Individual Task Breakdown by Design Stage

The coding scheme presents eight possible task types dependent on input entity, output entity, and the appearance of creative behaviour. These can be classified by design stage and by study, as shown in Table 61 and Figure 40.

Table 61: Individual task proportions in early and late stage design (Studies one and two). N.B. Data does not contain expert tasks

Task type	Creative/Non-creative	Early-stage proportion (%)		Later-stage proportion (%)	
		Study 1	Study 2	Study 1	Study 2
I → I	Creative	34.6	56.1	2.07	4.26
I → I	Non-creative	38.0	30.1	8.44	13.5
A → A	Creative	0.00	0.00	7.12	4.75
A → A	Non-creative	0.00	0.00	30.2	41.9
I → A	Creative	10.0	5.71	12.0	10.5
I → A	Non-creative	7.08	2.53	13.9	16.7
A → I	Creative	4.87	5.61	6.59	3.12
A → I	Non-creative	5.46	0.00	19.7	5.30

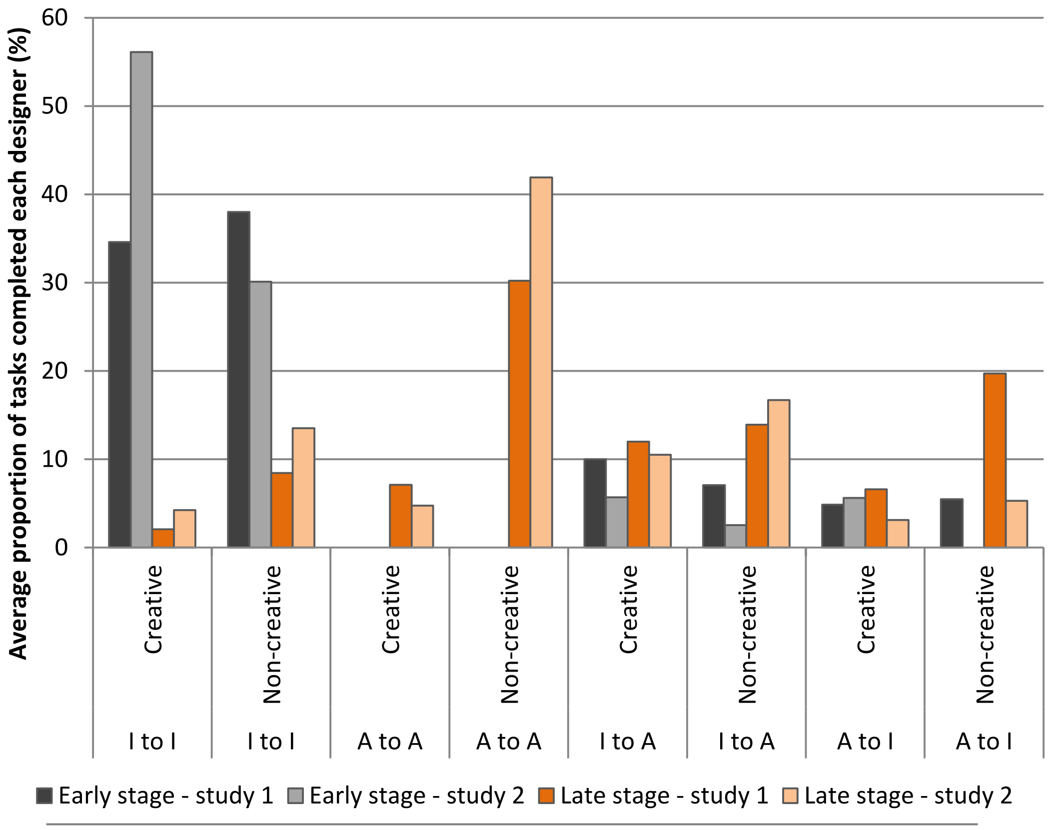


Figure 40: Proportions of task types completed by each designer in early and late stages

It is particularly clear in the early stages that within-entity information tasks are in a majority (see *[I → I]* and *[A → A]* categories; Table 61; Figure 40). In addition, it is clear that designers often display creative behaviour during these tasks, in a similar proportion to non-creative in the case of study one, and a majority in study two. Of the other tasks, the cross-entity types (see *[I → A]* and *[A → I]* categories; Table 61; Figure 40) are consistently present with a relatively low proportion, both in terms of creative and non-creative behaviour. There is a slight predominance of creative behaviour in information to application tasks types (see *creative [I → A]* in comparison to *creative [A → I]*), although this is not significantly higher than application to information tasks. As expected due to the definition of early stage design as focused on function rather than structure, there are few occurrences of application-output tasks, and none of within-entity application type *[A → A]*.

During later stages, within-entity application tasks are in a high majority, but only in terms of non-creative task behaviour. Creative behaviour is relatively low throughout, with a highest proportion in information to application tasks.

The separation between information and application focus between early and late stage design is as clear as previously presented (see Section 9.3). Here however, it is possible to discern further patterns between design stages.

While early-stage design is dominated by information, single-entity tasks (I → I type; Figure 40) with a high proportion of both creative and non-creative behaviour. In later-stages, not only can a swing towards application, single-entity tasks be seen (A → A type; Figure 40), but so can a swing to non-creative behaviour within (e.g. study 1; A →A type task; 7.12% creative, 30.2% non-creative; Table 61). This demonstrates a clear preference for both creative behaviour and task type between design process stages; at later points designers are concerned primarily with development of the physical design (as is to be expected given the stage focus on structure), and also complete these tasks in a primarily non-creative manner.

This non-creative focus proposes multiple discussions. First, perhaps due to the design situation of later-stages or the nature of the tasks, creative behaviour is not a necessity to progression in the case of these tasks. Second, as will be discussed in Chapter 11, there are arguments to be made for the importance of non-creative behaviour at appropriate points within the design process, where a creative process may even prove detrimental to the requirements of the specific situation.

Looking specifically at cross-entity tasks, the data only partially follows previously identified trends. In the case of both *[I → A]* and *[A → I]* type tasks, designers complete a higher proportion of non-creative tasks than creative during later stages than they do during early (e.g. 13.9% non-creative [I → A] later-stage, 7.08% non-creative *[I →A]* later-stage; study 1; Table 61). However, the proportion of creative tasks remains reasonably constant throughout, even rising in the case of later-stage, *[I → A]* type tasks. In Section 8.5, a pattern was identified of more frequent creative behaviour within cross-entity type tasks. This data augments that finding with the knowledge that these cross-entity task types are consistently completed creatively throughout the design process, and indeed form the primary proportion of creative behaviour during the later-stages of design.

This data therefore presents the findings that:

Twelve: *Within later-stages, designers generally concentrate on non-creative methods of behaviour and structural development of the design.*

Thirteen: *Cross-entity type tasks are consistently creative throughout the entirety of the design process; in a minority during early-stage design, and a majority during later-stage design, when compared to within-entity type tasks.*

9.5 Creative Behaviour through the Design Process

An advantage of the coding scheme when applied to a freely proceeding design process (as occurred in study one) is the ability to track the appearance of creative behaviour over time, in this case measured through task occurrence. This allows a more visual method of analysis of the appearance of creative behaviour.

By representing the occurrence of creative behaviour as an upward stroke and of non-creative behaviour as a downward stroke, Figure 41 demonstrates the creative process of each designer within study one as they progressed through the design process. It is of particular interest that two distinct groups can be formed based on lines of best fit placed along these traces (Table 62).

In the case of designers 1A, 1C and 1D, a linear trendline produces a good approximation of the data. In the case of designers 1B, 1E, 1F and 1G, a second order polynomial trendline is required to produce a good representation. On Figure 41 these two groups can be seen through those that follow an approximate upwards trend within the first third, and those that follow a general downward trend throughout. What is interesting about these groupings is that of those who require a polynomial trendline for a good representation of the data, three of the four follow an effectuating approach (designers 1B, 1F, 1G effectuating; 1E astute); while two out of three of those well represented by a linear trendline are primarily astute (designers 1A and 1C astute; 1D effectuating).

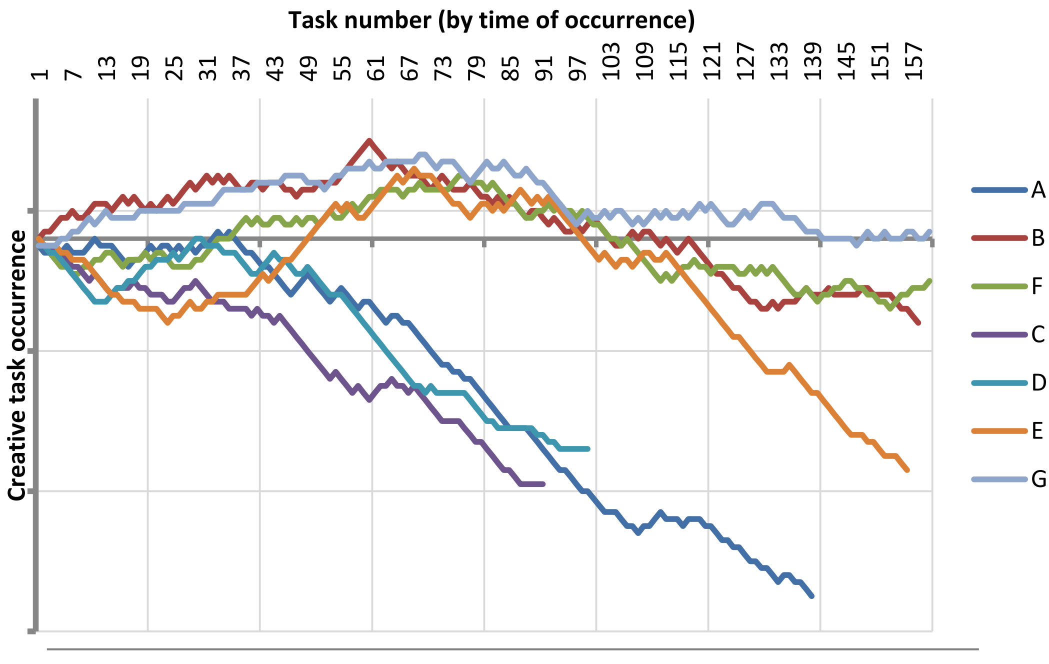


Figure 41: Trace of creative task occurrence (Study one)

Table 62: Coefficient of determination of creative behaviour trendlines (Study one)

Participant	Coefficient of determination (R^2 = ...)		Late-stage approach	Ratio: Creative / non-creative
	Linear	Polynomial (2nd Order)		
1A	0.977	0.965	Astute	0.338
1B	0.606	0.885	Effectuating	0.813
1C	0.953	0.977	Astute	0.300
1D	0.792	0.915	Effectuating	0.333
1E	0.250	0.817	Astute	0.560
1F	0.157	0.748	Effectuating	0.622
1G	0.0971	0.707	Effectuating	0.793

In real terms, a polynomial trendline represents behaviour of the designer which is more often creative in early-stage design than non-creative, before a switch towards a majority of non-creative behaviour at later stages of the design process. Thus designers whose processes are best represented by a polynomial trendline are also those who demonstrate more creative behaviour on the whole. Coupled with the data that designers best represented by a polynomial trendline usually follow an effectuating approach rather than an astute, this data provides a tentative suggestion that those designers who are most creative throughout the design process are also effectuating in later stages. Thus the following tentative finding can be made, discussed in Section 11.4:

Fourteen: *More creative designers typically follow an effectuating approach during later-stage design processes.*

9.5.1 Stage-Based Creative Behaviour

As formalised in findings Five and Twelve, the occurrence of creative behaviour decreases as the design process continues. Looking specifically at study one, more detail can be added.

Table 63 shows the occurrence of tasks within each design stage according to the definitions used within this work (see Section 3.3), as well as the proportion of tasks completed creatively for each. As demonstrated, conceptual design contains the highest proportion of creative behaviour (51.6%; Table 63), followed by a small margin by embodiment design (42.2%) and a big margin to detail design (10.9%).

Given these proportions, it is clear that although creative behaviour does decrease as design progresses, it will decrease more dramatically in some areas than others. Although both classified within the *later stages of design*, embodiment and detail design have a different focus; the former developed the behaviour and preliminary structure of the system, while the latter develops and finalises only the structure. The data would then suggest that specific areas of later-stage design exist in which designers typically display higher occurrence of creative behaviour. Following the definition of embodiment design given in this work, this data provides the following finding, discussed in Section 11.4:

Fifteen: *During later-stage design, creative behaviour primarily concerns the determination of system behaviour and preliminary structure.*

Table 63: Proportions of tasks in each design stage (in brackets, relative creative proportion) (Study one)

Participant	Task proportion (%)		
	Concept	Embodiment	Detail
1A	29.1 (36.7)	50.5 (28.8)	20.4 (0.00)
1B	29.3 (64.7)	48.3 (42.9)	22.4 (23.1)
1C	23.1 (26.7)	41.5 (29.6)	35.4 (13.0)
1D	35.0 (42.9)	20.0 (41.7)	45.0 (3.70)
1E	28.2 (48.5)	39.3 (50.0)	32.5 (7.90)
1F	23.3 (58.8)	40.4 (49.2)	36.3 (13.2)
1G	23.3 (68.0)	53.8 (46.4)	22.1 (13.0)
Average	**27.4 (51.6)**	**42.0 (42.2)**	**30.6 (10.9)**

Further observations can be made by comparing the creative proportion of each designer with the average for the group. Table 64 and Figure 42 present this data as a percentage of the group average, thus designer 1A, within concept tasks, completed a proportion equal to 71.9% of the group mean; and designer 1E, in embodiment tasks, completed a proportion equal to 119% of the group mean. A value greater than 100% therefore indicates a designer who is more creative than average within each stage, or through the process as a whole as indicated.

There are several observations to be made from this data. First, those designers who are more creative in one stage are often more creative in all (see participants 1B, 1F and 1G). Designers 1C and 1E break this trend, each demonstrating more creative behaviour than average in a single stage (detail and embodiment respectively), although neither was more creative than the group average on the whole.

Similarly to finding fourteen, those designers who are creative more than the group mean (designers 1B, 1F and 1G in Figure 42, coloured orange) all completed a primarily effectuating approach in later-stage design, while three of the four designers with lower than average creative occurrence followed a later-stage astute approach.

Support for two findings can be made from this data. First, that some consistency exists in quantity of creative behaviour between stages (i.e. should a designer be more creative in one stage they are often more creative in all) supports the notion of varying levels of "creativity" inherent in the behaviour of designers. In other words, and summarising finding two, different designers will demonstrate varying levels of creative behaviour within their design process. Second, and supporting finding fourteen, those designers who display creative behaviour more than average tend to follow an effectuating approach in later stage design.

Table 64: Proportion of creative tasks, against study mean proportion of creative tasks

Participant	Creative tasks, as ratio against group mean (%)			Average (%)	Primary Late-stage Approach
	Concept	Embodiment	Detail		
1A	71.9	68.4	0.00	46.8	Astute
1B	127	102	212	147	Effectuating
1C	52.3	70.2	120	80.7	Astute
1D	84.0	98.7	34.0	72.2	Effectuating
1E	95.1	119	72.4	95.3	Astute
1F	115	117	121	118	Effectuating
1G	133	110	120	121	Effectuating

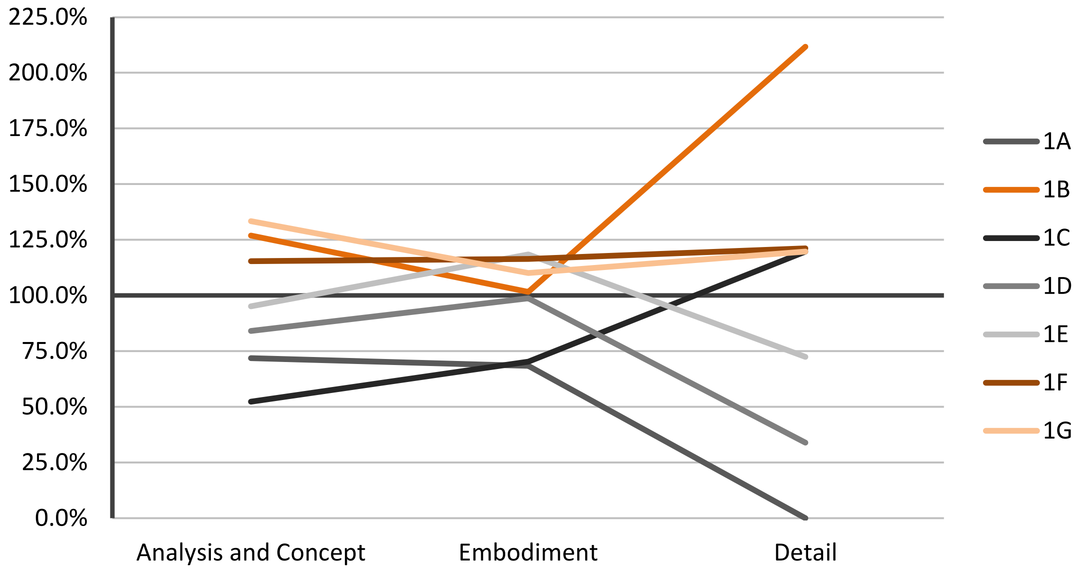


Figure 42: Creative task occurrence of study 1 designers, as ratio against group average

9.6 Creative Behaviour between Design Stages

Although different designers display different primary approaches during later-stage design (either *astute* or *effectuating*), there is no reason to assume that this approach would be their only mode of creative behaviour throughout the design process.

Table 65 and Table 66 present the proportion of tasks displaying creative behaviour throughout design stages, with the relative proportion of information-type creative (astute) and application-type creative (effectuating) tasks in each. This provides information of frequency of the appearance of each approach through the design process in general terms, for the moment ignoring individual difference.

Both tables show very similar proportions of both astute and effectuating task types in each stage of studies one and two, with a singular exception of the embodiment stage of study one. At this point, although the proportion of astute tasks has dropped, in line with the finding that creative behaviour drops through the design process (finding five), the proportion of effectuating tasks remains high (27.6% embodiment astute; 48.4% embodiment effectuating; Table 65). Within the detail stage, in line with finding five, twelve and fifteen, detail design presents little by way of creative behaviour.

This difference is not seen in the data for study two. This could be either a result of methodology, or of the limits of analysis. As study two was completed in stages specifically designed to induce tasks belonging to relevant stages of the design process and was heavily restricted by time, designers were indirectly discouraged from iteration and exploration within each. Particularly during the later-stage portion of the process (in which the designers were prompted to finalise as much of the design as possible) creative behaviour may have been methodologically inhibited, resulting in a lower-than-realistic value for later-stage creative proportion. This methodological limitation in realism and scope is discussed in Chapter 11. The second possibility is due to the necessity for analysis through categorisation as “late-stage” rather than “embodiment” and “detail”. As the study was limited in time, designers completed far fewer tasks than in the same stages of study one. As a result, the lower quantity of tasks prevents high granularity of data and necessitates a less-populated category. This is also discussed in Chapter 11.

Considering then only the pattern seen in Table 65 for study one, the consistent proportion of effectuating tasks through concept and embodiment design suggests a higher suitability of application-type tasks for creative behaviour within embodiment. As discussed in Section 11.4, that designers maintain creative behaviour primarily in one task type in one stage of design presents the finding that:

Sixteen: *A higher proportion of creative behaviour occurs in application-type tasks through both concept and embodiment design.*

Table 65: Creative task proportions through design stages (Study one)

Design Stage	Overall average proportion (%)	Proportion of creative tasks of different types through stages (%)	
		Astute	Effectuating
Analysis and Concept (early stage)	51.6	47.2	55.4
Embodiment	42.2	27.6	48.4
Detail	10.9	12.3	10.9

Table 66: Creative task proportions through design stages (Study two)

Design Stage	Overall average proportion (%)	Proportion of creative tasks of different types through stages (%)	
		Astute	Effectuating
Early Stage	66.7	60.6	66.7
Late Stage	20.9	21.7	20.7

Further observations can be made by looking specifically at the approaches of the participants in both the late and early stages of the process. Table 67 shows late-stage approach, along with early-stage approach as observed in the same manner.

What is striking in this data is that in many cases the approach followed by the designer changes from early stage to later. For example, despite being effectuating in later-stages, designer 1F is primarily astute in early. Similarly, within early stages designers 1A, 1B and 1G display such similar proportions of astute and effectuating tasks that description according to any single approach is unfair – hence their description as "balanced". It is interesting, however, that although there are many examples of designers becoming more effectuating towards later stages (Designers 1B, 1G; balanced approach to effectuating approach; Designers 1F, 2B, 2I; astute to effectuating), there is only one example of a designer becoming more astute (in the case of designer 1A).

This data therefore augments the findings of creative style presented in Chapter 8 with stage-dependent context; designers may follow different approaches based on personal preference of some form rather than on project-dependence, but the approaches followed are not fixed per designer. Perhaps due to the design situation, task types, or personal preference and experience, a designer is able to alter their approach throughout the design process. This is further discussed in Section 11.4, and creates the finding that:

Seventeen: *Despite preference for one over the other, a designer's creative approach can vary through the design process. Some designers remain astute in later-stage design, while others become effectuating.*

Table 67: Comparison of creative approach between early and late-stage design (Studies 1 and 2)

	Late-stage		Early-stage			
	Ratio Eff/Ast	Approach	Astute proportion (%)	Effectuating proportion (%)	Ratio Eff/Ast	Approach
1A	0.722	Astute	37.0	33.3	0.900	Balanced
1B	1.91	Effectuating	64.5	66.7	1.03	Balanced
1C	0.750	Astute	33.3	0.00	0.00	Astute
1D	--	Effectuating	25.0	100	4.00	Effectuating
1E	0.646	Astute	42.3	71.4	1.69	Effectuating
1F	3.11	Effectuating	60.0	50.0	0.833	Astute
1G	1.98	Effectuating	68.4	66.7	0.974	Balanced
2A	--	Effectuating	66.7	100	1.50	Effectuating
2B	--	Effectuating	40.0	0.00	0.00	Astute
2C	0.800	Astute	50.0	0.00	0.00	Astute
2D	1.60	Effectuating	--*	--*	--*	--*
2E	--	Effectuating	75.0	100	1.33	Effectuating
2F	0.417	Astute	55.6	33.3	0.600	Astute
2G	0.200	Astute	70.0	0.00	0.00	Astute
2H	0.750	Astute	71.4	50.0	0.700	Astute
2I	--	Effectuating	66.7	0.00	0.00	Astute
2J	--	Standard	66.7	0.00	0.00	Astute
2K	--	Standard	100	100	1.00	Balanced
2L	--	Standard	85.7	0.00	0.00	Astute
Average	1.17	(Effectuating)			0.809	(Astute)

9.7 Design Stage Focus and Quality

Similar to the analysis in Section 8.7, the design stage behaviour of the designers can be studied in context of the final quality of their designs. Using identical quality data, correlations have been found between quality as judged by expert designers and several variables, as presented in Table 68.

These data present several interesting implications for the judgement of quality of a design.

First, those designers who demonstrate a higher creative information-type task focus in early stage design, and those who demonstrate a higher application-type task focus in later stage design, are also those who produced the highest quality results. Given finding eleven, designers naturally focus on these types in early and late stages respectively, this would suggest that they are intuitively following effective behavioural patterns – a design process that switches from information focus to application focus will lead to better results.

Table 68: Correlation between expert quality judgement and task occurrences (Studies 1 and 2)

First Variable		**Second Variable**	**Correlation (ρ=...)**	**Significance (p=...)**
Expert quality judgement	1	Early stage astute type task proportion	0.701	0.00809
	2	Early stage creative task proportion	0.542	0.0425
	3	Late stage application task proportion	0.480	0.0510
	4	Late stage effectuating type task proportion	0.495	0.0434
	5	Late stage creative task proportion	0.471	0.0517

Second, the two correlations relating to creative task proportions show quite opposite effects of creative behaviour. In both stages of design, quality is increased through a focus on creative behaviour. However, in early stages this is through the maximisation of creative information-type tasks, and in the later-stages this is through the maximisation of application-type tasks. As will be discussed, this is likely more subtle than the data would immediately suggest; rather than being a case of creative behaviour being *better* or *worse* at different points in the design process, this data suggests suitability of creative behaviour dependent on design situation and desired effect – creative behaviour at different points of the design process will have varying fundamental consequences for the final design. At a base level however, this data presents the following finding, elaborated and discussed in Section 11.4:

Eighteen: *By expert judgement, high quality is more dependent on later-stage creative behaviour (correlations 4 and 5; Table 68), a late-stage focus on application-type tasks (correlation 3), and an early-stage focus on creative information-type tasks (correlation 1).*

It is also noteworthy that no other significant correlations were found relating expert-judged quality to designer behaviour in the stages of design. This could be indicative of a lack of relationship existing, and hence the correlations found indicating the only behavioural traits that lead to quality as judged by experts. Alternatively, it could be indicative of the requirement for further study with a larger data-set, to increase the sample size on which correlation can be assessed. Such extensions to the research are a target for future work, with the correlations found being the main focus of this work.

9.8 Summary: Creative Design Process Behaviour

This chapter has presented findings concerning behaviour through the design process, with a particular focus on comparison between early-stage and late-stage design. These findings are listed in Table 69 and discussed in Chapter 11. Note that the second column indicates whether the finding represents new knowledge or confirmation of current or expected knowledge within the field.

This chapter also concludes Section Two of the thesis as a whole, following the thesis structure set in Table 13. It has presented an additional nine findings relating specifically to the behaviour of designers within the engineering design process.

The following chapter then begins Section Three of the thesis, and discusses in more detail the role of experience and context on variation in designer behaviour.

Table 69: Summary of findings on the theme of creative design process behaviour

Finding Number	New finding / Confirming finding	
11	Confirming	*Through the stages of design, there is a general shift in focus from information-type tasks to application-type tasks.*
12	Confirming	*Within later-stages, designers generally concentrate on non-creative methods of behaviour and structural development of the design.*
13	New	*Cross-entity tasks are consistently creative throughout the entirety of the design process; in a minority during early-stage design, and a majority during later-stage design, when compared to within-entity type tasks.*
14	New	*More creative designers typically follow an effectuating approach during later-stage design processes.*
15	Confirming	*During later-stage design, creative behaviour primarily concerns the determination of system behaviour and preliminary structure.*
16	New	*A higher proportion of creative behaviour occurs in application-type tasks through both concept and embodiment design.*
17	Confirming	*Despite preference for one over the other, a designer's creative approach can vary through the design process. Some designers remain astute in later-stage design, while others become effectuating.*
18	New	*By expert judgement, high quality is more dependent on later-stage creative behaviour, a late-stage focus on application-type tasks, and an early-stage focus on creative information-type tasks.*

Chapter 10: Results: Expertise and Design Context

While chapters 7, 8 and 9 report the primary analysis method and findings of the research, there is another element that must be approached. In addition to presenting results, the work must also present validity in the real-life, industry design process.

It is to this end that Chapter 10 proceeds, forming the third section of the thesis structure as presented in Chapter 5. As stated at an early point within this thesis, there is high context dependence in the study of creativity, and in the study of designer behaviour. It is therefore necessary to study the role of context on creativity and behaviour in each of the studies that has been completed so far.

Chapter 10 presents findings to this end in two streams. The first performs a comparison of expert and non-expert behaviour within studies one and two. The second performs study three, a direct observation of designers working within industry. Through the additional understanding gained from these analyses, the role of context on designer behaviour can be clarified.

This chapter also forms the conclusion of presentation of results within this thesis. In total, twenty-six findings relating to designer behaviour and creative behaviour are presented, with particular consideration of the role of later-stage design, and are discussed in detail in Chapter 11.

10.1 Introduction

This chapter is presented in two discrete sections, both with the goal of presenting some of the wider considerations when studying designer behaviour. The first of these looks at the difference between expert and non-expert processes – due to the group of participants within study two, a comparison between each can be made on data collected from an identical design situation. The second section of this chapter looks at the wider impact of working within industry on designer behaviour. This is completed through study three, an observational study of industry engineers working on industry projects in an industry environment.

Study Four itself also occurs in two parts. The first of these looks at the context of the projects completed by the participants, to assess the comparability of each to studies one and two, and to identify and begin to understand the influencers on designer behaviour that appear in the specific context of industry. The second part then used this knowledge to perform a more detailed comparison of designer behaviour between three of the projects observed in industry, and the results of studies one and two. As the participants in study three also participated in study two, direct comparison can be made.

At its core this chapter provides the understanding necessary to provide some triangulation of validity of results in an industry context, through comparison with the other studies within the thesis. Both studies one and two were designed to mimic an engineering design process, and so are valid in terms of themselves and in a general sense. What is not known, and what is provided by this chapter, is how the findings of Chapters Eight and Nine must be tempered and altered when the behaviour of designers in an entirely realistic setting is considered.

As within Chapters 8 and 9, this chapter presents results from studies one and two. Table 70 provides a summary of these studies for clarity.

Table 70: Summary of studies one and two

	Study One	Study Two
Participants	7 undergraduate non-expert	10 undergraduate non-expert 4 industry expert (ave. 159 months) 2 industry non-expert (< 24 months)
Study type	Indirect observation Uncontrolled setting	Direct observation Controlled setting
Data	Logbook	Audio, video, screen capture, logbook, questionnaire
Brief	Varies dependent on participant	Identical for all participants
Length	22 weeks	4 hours
Team working	None	Some; unstudied

10.2 Expert and Non-Expert Comparison

This section of the chapter presents the results of studies one and two from a perspective of expert analysis, particularly in context of comparison between the expert participants against the non-expert participants. This is a common form of research, featuring prominently in design fields and beyond (Ahmed et al., 2003, Cash et al., 2013, Ericsson and Lehmann, 1996, Kavakli and Gero, 2003).

Within this work there are two purposes that this section meets. First, due to their explicit experience the study of experts provides a better example of realism in study. Second, as a number of experts and non-experts took part in the study some direct comparison can be made, highlighting the differences in behaviour that may denote expertise. Through these two strands this section provides both validity to results through realism, and additional benefit in the form of an additional layer of understanding.

Study two in particular is very supportive of this method, as it provided three distinct groups of varying immersion within industry. One group was entirely undergraduate-based (experienced non-experts; 14 participants), one group was expert (4 participants), and one group was based within industry, but of little formal experience at this point in their careers (2 participants). This final group can therefore also be considered experienced non-experts.

This section continues through comparison of the results of each of these groups when placed against the categories of results in Chapters Eight and Nine.

10.2.1 Creative Behaviour and Quality

Within this work, as within the wider research field, expertise is considered to refer to expert performance, and expert behaviour is therefore considered to be better than non-expert behaviour. Expert behaviour is then achieved through 10 years deliberate practice in a field (Ericsson et al., 1993), while any level of experience lower is considered "experienced" but "non-expert". This performance increase is thought to manifest as an ability to frequently produce higher quality solutions, and to follow more effective solution strategies (Chi, 2006, Simon and Chase, 1973). Following this principle, any behaviour that is common or frequent within the process of expert designers can be recognised as "better" behaviour. Throughout this section, the term "expert" refers to those participants who can be expected to display expert performance, while "non-expert" refers to any other participant – all of whom had some experience in the field, either through university training alone, or through training and industry exposure.

To make the assumption that experts perform better than non-experts with confidence, this work can study the results from each quality assessment method introduced in Section 7.6. According to theory the experts should each produce designs that are of better quality than the students.

This is presented by Table 71, which shows that experts were judged to produce better designs by both assessment metrics. Additionally, in the expert-judged assessment method, only the "concept" category resulted in a higher score for the non-experts than the experts.

It can therefore certainly be concluded in this case that the assumption of expert superiority in output is likely. Although the difference in scores is not large, the fact that by multiple methods of assessment the results of experts were proven superior gives the finding:

Nineteen: *In the same design situation, the design solutions of experts are often better than non-experts, both according to metric-based assessment and expert judgement.*

Table 71: Quality of designs of experts and non-experts (Study two)

Participant group	Average expert-judged quality	Average expert-judged creativity	Average metric-judged quality
Study 2 non-expert	2.92	3.46	0.81
Study 2 expert	3.25	3.50	1.25
Expert/non-expert ratio	1.11	1.01	1.54

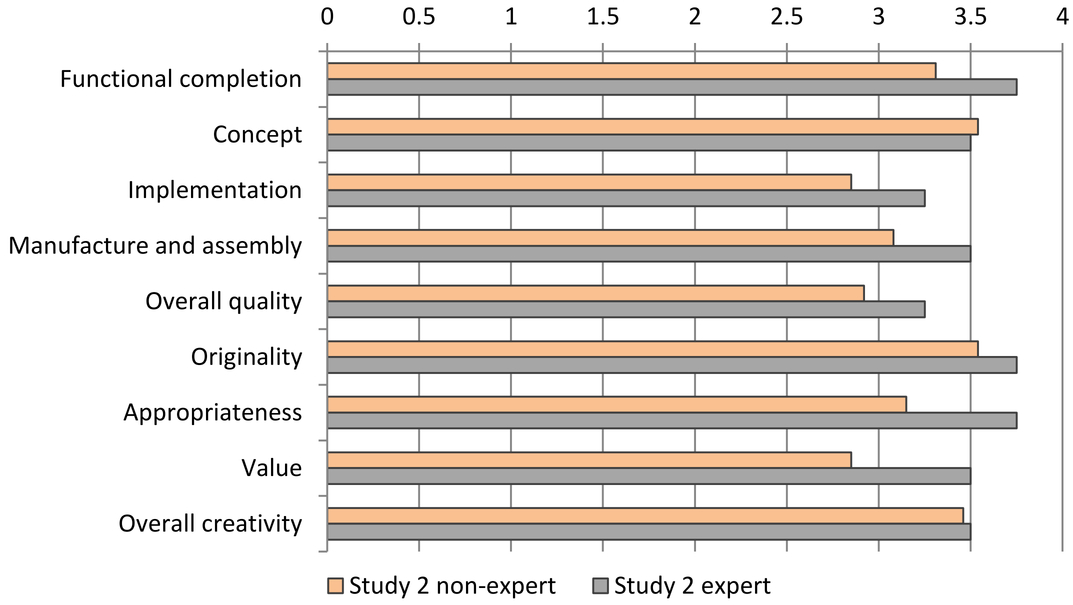


Figure 43: Ratings of designs produced by experts and non-experts (study 2)

Interestingly, by each sub-category under the definition of creativity the judges determined the experts to be the more creative (Figure 43). For overall creativity, however, they determined little difference. By definitions within literature it can then be expected that the experts will demonstrate solution strategies that are more conducive to producing a creative result, but that their output will not necessarily be determined as creative by the observer.

As creativity within this work, as within much of literature, is defined by these terms; this then also gives the finding:

Twenty: *By the assessment of an experienced human observer, when based against the definition of creative products, expert designers will produce a more creative solution than non-experts in an identical design situation.*

10.2.2 Creativity within the Design Process

As within Chapter 8, the first area of focus in study of expert behaviour within this chapter is the appearance of creative behaviour in individual processes (shown in Table 72).

Experts demonstrated a similar proportion of creative behaviour to non-experts within the later stage design process, with a value of 28.6%. When compared to study one this is a very similar value, suggesting that experts demonstrate an equal occurrence of creative behaviour to non-experts. However, study one created a quite different design situation to study two, particularly in the pressure caused by very limited time. It is perhaps then fairer to compare the results of experts in this case not to study one but to the non-experts in study two.

Table 72: Creative proportions of expert and non-expert groups (later-stage only)

Participant group	Creative proportion (%)	Non-creative proportion (%)	Ratio (creative/non-creative)
Study 1 non-expert	29.5	70.5	0.418
Study 2 university non-expert	21.8	78.2	0.280
Study 2 industry non-expert	8.00	92.0	0.0870
Study 2 expert	28.6	71.4	0.400

In this case the experts performed significantly more tasks in a creative way with an average value nearly 7% higher. Though not conclusive, there is certainly merit to the argument that experts are more frequently creative than non-experts.

Surprisingly, both the university-based non-expert and expert groups performed much better than the industry non-expert group, who demonstrated very little by way of creative behaviour. There is no clear explanation for this – they were in the same design situation, completing the same brief, under the same conditions. One possible explanation is in their tool use throughout section 3 of study 2. Whereas the non-experts at the University all used solely sketches to produce their designs, both industry non-experts used CAD tools. Given their relative lack of experience of these tools, there is possibility that their use pushed the designers to the non-creative. Such observations are a subject for further work.

Given these points, the following finding can be stated about expert creative behaviour:

Twenty-One: *Experts demonstrate creative behaviour in their tasks, with a potential higher proportion to non-experts.*

10.2.3 Creative Approach in Later-Stage Design

Chapter 8 demonstrated the appearance of two different creative approaches (an *astute* approach or an *effectuating* approach), determined through the type of creative task that designers more frequently completed. Both of these approaches appeared in approximately equal proportion; no clear majority emerged when comparing all participants. This is not the case when the experts are grouped.

While a near even split of approaches exists in the case of each group of non-experts (Table 73), near-all experts followed an effectuating approach within section 3 of study two. The exception to this was participant 2N, who completed 100% of their information tasks in a creative manner, and so was classed as following an astute approach. However, as they completed only one information-type task and several application-type tasks, this is perhaps not strong observation.

Table 73: Creative approaches of expert and non-expert designers

Participant group	Number following astute approach	Number following effectuating approach	Number following standard approach
Study 1 non-expert	3	4	0
Study 2 university non-expert	4	5	3
Study 2 industry non-expert	0	1	1
Study 2 expert	1	3	0

Finding Three demonstrated that either approach could appear regardless of task, placing the major causal factor in this case (in which design context is identical) as the designer. There are therefore two options that may explain for the effectuating approach majority of experts. Either the experts are by coincidence all those who naturally follow an effectuating approach; or they all followed an effectuating approach by choice (all be it likely a sub-conscious process due to training). This is an argument that would need further study to conclude fully, but can be elaborated by looking more deeply at the proportions of tasks completed by the expert designers.

In reality, it is not surprising that experts were more often creative in application type tasks, given the very small proportion of information-type tasks that appeared (Table 74). Where non-experts under the same study conditions completed 77.3% of their process through application type tasks, experts were a full 12.5% higher.

Table 74: Output task types as completed by expert and non-experts (later-stage)

Participant Group	Application type task proportion	Information type task proportion
Study 1 non-expert	60.9	39.1
Study 2 university non-expert	77.3	22.7
Study 2 industry non-expert	100	0.00
Study 2 expert	89.8	10.2

This imbalance in task type is more stark than the appearance of creative behaviour – experts did not, through a lack of choice or a lack of personal necessity – develop their information sources at all throughout the later-stage design process. They each took their resources as-is, and manipulated them into a solution. This more strongly suggests a pattern in behaviour in the experts. All focused on only one type of task, while non-experts completed tasks of both types.

As a trait of expert behaviour, a pattern of focus solely on application-type tasks in later-stages (and hence creative behaviour within) also suggests links to examples of "better" behaviour. Taking that experts produce better results that non-experts, and that they should through practice follow better solution strategies (see Section 4.3), a focus on application type tasks can be said to represent a "better" process than a focus on information-type tasks. This is discussed within Chapter 11.

These points give two findings, discussed in Sections 0 and 11.4:

Twenty-Two: *Experts have a near complete focus on application-type tasks in later-stage design.*

Twenty-Three: *Experts consistently follow an effectuating approach in later-stage design, suggesting superiority or higher approach suitability.*

It is also interesting to note that those designers in study two all had a much higher application-focus than those in study one. The reason for this could be through the design situation, in that study one was far less restricted in process and time. As discussed in Chapter 11, there is potential for the strict conditions to have focused the designers onto a higher rate of progress within their process, which manifested in a high application-type task focus. This more tentative suggestion would imply a better form of behaviour to effectively and efficiently reach a solution in later-stage design.

10.2.4 Creative Task Transformation Types

Section 8.5 demonstrates a strong pattern of creative behaviour occurring in cross-entity type tasks. This is no different when considering experts as a separate entity; as seen in Table 75, all groups of designers regardless of experience are more often creative when completing cross-entity type tasks.

Table 75: Creative transformation approaches for expert and non-expert designers (later-stage)

Participant Group	Cross-entity approach	Within-entity approach	Approach proportion majority*
Study 1 non-expert	6	1	16.8
Study 2 university non-expert	8	0	20.4
Study 2 industry non-expert	1	0	40.0
Study 2 expert	4	0	31.8

***N.B.** Approach proportion majority is the difference between cross-entity type creative task occurrence and within-entity type creative task occurrence. A higher number indicates that a higher relative proportion of cross-entity type creative tasks was completed. Actual data for this is shown in Table 76.

What is particularly interesting is the majority shown by the experts and industry non-experts. In truth, the industry non-experts displayed very little creative behaviour, which has the effect of inflating the approach majority. Should there have been more data points, there may well have been a normalising effect that reduced the proportion to similar levels to the other groups.

The experts did, however, have sufficient data points for comparison. There is similar behaviour shown by both non-experts and experts, but with the experts providing a higher majority. While the non-experts within study two had a difference between approach proportions of 20.4%, the experts were 1.5 times higher with 31.8%. This provides the finding that:

Twenty-Four: *Experts are more often creative in cross-entity type tasks, to a higher proportion than non-experts.*

Again assuming, as evidence suggests, that expert behaviour is superior to non-expert behaviour, there is a likelihood of creative behaviour within cross-entity tasks being a characteristic of good practice in design. This is further discussed in Section 11.4, and provides the finding that:

Twenty-Five: *Better design behaviour can be characterised by a majority proportion of creative cross-entity tasks.*

Further, there is a difference in approach majority between those non-experts within study one and those within study two. The more likely cause for this is study methodology, and provides a suggestion of insight into the effect of the design situation on designer behaviour. When subject to lower pressure and restriction (as in study one), the non-expert designers were more often creative in within entity tasks (see Table 76).

Table 76: Average creative proportions by transformation type

Participant Group	Cross-entity creative type task proportion	Within-entity creative type task proportion
Study 1 non-expert	37.1	20.3
Study 2 university non-expert	34.9	14.5
Study 2 industry non-expert	40.0	0.00
Study 2 expert	50.0	18.2

10.2.5 Task Types within Later-Stage Design

All designers were free within their process to complete any type of task, so long as it led towards a solution. Finding eleven has already demonstrated that there is a particular focus on application-type tasks in later stage design. When considering experts separately to non-experts, this finding only strengthens.

In addition to these results, the transformation types of the experts and non-experts can be studied. The clearest difference in the behaviour of the study two participants within Table 77 is the increased within-entity task proportion when compared to those within study one (63.9% within-entity proportion non-experts, 67.3% experts, study two; 45.5% non-experts, study one). As mentioned in other sections, a difference of this nature could be a result of study methodology, and could imply the effect of design situation on designer behaviour.

Although there is too little information to state a finding with high confidence, there have been other examples presented of possible effects of design situation on designer behaviour. Working within a higher pressure and time-limited design context may cause the designers to alter the way in which they proceed, as is discussed in Chapter 11.

Table 77: Transformation task types as completed by expert and non-experts (later-stage)

Participant Group	Within-entity type task proportion	Cross-entity type task proportion
Study 1 non-expert	45.5	54.5
Study 2 university non-expert	63.9	36.1
Study 2 industry non-expert	80.0	20.0
Study 2 expert	67.3	32.7

10.2.6 Creative Style Analysis

Section 8.4.1 presented some correlations of creative behaviour with a creative style test (the KAI scale). There were too few experts within this study to identify significant correlations with their results, but there is still a point of validity to be made.

Those who score higher on the KAI test are considered to be creative in a different manner to those at the lower end of the scale, and to be generally of higher creative level as understood by traditional theory. Should the experts all then demonstrate a higher KAI score than the non-experts, a coincidental common trait of personality could be the reason for their differences in behaviour.

Looking at Table 78, all groups have very similar scores. They also reflect typical theory, which states that engineering as a field should show a slightly higher score than average due its requirement for some flexibility in forming solutions (Kirton and Fender, 1982); and are suitably similar that personality differences will not be significant. Hence according to the *average* of the groups, there is no difference in creative style score.

The improvement in expert results is therefore not due to their inherent creative style score being higher or lower; rather more likely being to be due to some trait of expertise and practice.

Table 78: Average creative style test scores for experts and non-experts

Participant Group	Average creative style test score
Study 1 non-expert	97.6
Study 2 university non-expert	103
Study 2 industry non-expert	99.0
Study 2 expert	102

10.2.7 Summary: Expert and Non-Expert Behaviour

This initial section of Chapter 10 has studied the differences in behaviour as displayed by experts and non-experts, working within an identical design situation, and across design situations. In this way it begins to address one shortcoming of studies one and two, the failure to account explicitly for the inexperience of the non-experts in analysis of results, and the role that their experience plays in the process that they complete. The findings of this section are listed in Table 79. Note that the second column indicates whether the finding represents new knowledge or confirmation of current or expected knowledge within the field.

Another shortfall of studies one and two is the lack of industry context that they consider. The study of experts within an industrial setting of study two increases confidence in results to an extent, but are still only entirely valid for the study design brief and a highly accelerated design process.

To increase confidence in all results presented to this point, it is necessary to consider the role of industry context in more detail. It is to this goal that Chapter 10 continues.

Table 79: Findings relating to expert and non-expert comparison

Finding Number	New finding / Confirming finding	Finding
19	Confirming	*In the same design situation, the design solutions of experts are often better than non-experts, both according to metric-based assessment and expert judgement.*
20	Confirming	*By the assessment of an experienced human observer, when based against the definition of creative products, expert designers will produce a more creative solution than non-experts in an identical design situation.*
21	Confirming	*Experts demonstrate creative behaviour in their tasks, with a potential higher proportion to non-experts.*
22	New	*Experts have a near complete focus on application-type tasks in later-stage design.*
23	New	*Experts consistently follow an effectuating approach in later-stage design, suggesting superiority or higher approach suitability.*
24	New	*Experts are more often creative in cross-entity type tasks, to a higher proportion than non-experts.*
25	New	*Better design behaviour can be characterised by a majority proportion of creative cross-entity tasks.*

10.3 Industrial Context

In Chapter 2 the four pillars of creativity of Rhodes (1961) were presented as a framework for understanding the behaviour of designers, implying that detailed understanding required consideration of the person, the process and the context as they develop a product. It was also stated at this point that although the influence of the creative context is important, the scope for research that it created was too substantial to lie within this research project. Instead, this thesis explores the pillars of person and process, and their build up towards the product. However, there is one element of the context that is highly beneficial to consider.

Study one involved only undergraduate participants, although they were working freely on engineering-design based projects. Study two involved both undergraduate and industry designers and took place in appropriate surroundings, but was limited in the project brief. One particular strength of ethnographic study is its realism (Ahmed et al., 2003, Robson, 2002) in process and surroundings; the work that designers complete within it is representative of real life design situations. The same cannot be said conclusively of either study one or study two; and is a highly valuable subject to address.

There is some literature demonstrating similarity in process between expert and non-expert (see Cash et al., 2013). There is also significant literature demonstrating difference between the two, such as that on expertise (see Cross, 2004b) and problem solution strategy (Ball et al., 1997). The results presented within Chapters Eight, Nine and Ten must therefore be qualified – a certain level of validity exists in their realism, but the effect of working within a realistic design situation must be approached.

It is from this step that significant further working can be developed. While results to this point have provided strong generalisations of designer behaviour and potentially useful traits, approaches and patterns, the detailed influences of real life industry processes open many new avenues for study (as will be demonstrated).

10.3.1 Study within Crown

Study Three involved recorded observation of designers working within Crown Holdings Inc. (referred to as “Crown” within this work), a global metal-packaging firm. Crown is a large company, with a global turnover of $8.5billion USD in 2012, and 22,000 employees . Observation occurred in their UK Research and Development site (“Crown Technologies”), the area of the business that develops new products and manufacturing processes.

The purpose of this study was to observe the behaviour of designers in an industry setting, in order to inform understanding of the results presented in Chapters 7 and 8 and to begin to understand the role of design situation and realistic design context on behaviour.

Specifically, this study was performed to serve as realistic counterpoint to studies one and two, both of which have provided findings regarding designer behaviour. Both clearly provide findings within their own design contexts, but can only be generalised with care. Direct study in industry can improve understanding – the results are certainly representative of design in industry, and through understanding of the context that industry presents in contrast to studies one and two, the combined results can provide a more detailed and robust picture. The specific aims of study three were therefore to:

"Investigate the appearance of creative behaviour in later-stage engineering design processes within an industrial context"

"Allow comparison and understanding of the differences in creative behaviour as displayed between experts and non-experts, and between industry and non-industry settings."

In this way study three serves as the basis on which further work beyond the scope of this thesis can be built; Chapters Eight and Nine have presented results characterising creative and non-creative behaviour in later-stage type design, study three begins to explore the implication of detailed understanding of design context on these results.

10.3.2 Industrial Study Participants

The study took place with four designers based within Crown, three from the innovations department and one from engineering design. These departments are both highly design-focussed in their purpose within the company, but have quite different roles.

The role of the innovations department is, from the initial requirements of customers, to design new and innovative packaging. This will always involve a design element in terms of form and aesthetics, but often also includes design of novel mechanisms (such as for opening, closing or sealing), re-design to take advantage of new manufacturing technologies, or design optimisation to improve aspects such as pressure performance. The innovations team are required to take each project to a point of full proof-of-concept and feasibility, which will vary in scope from a simple look-alike prototype to complex testing and demonstrating of performance or safety criteria. Within their work they cover broad and significant segments of the design process, ranging from task analysis and concept design through to reasonably complex detail design.

The role of the engineering design department is two-fold. First, it is through their work that all bespoke machinery needed for manufacturing and testing is developed. Particularly in cases of novel packaging, realistic metal prototypes can only be made through the use of one-off manufacturing tools and machines. In other cases the engineering design team may need to produce a machine that demonstrates feasibility of manufacture, either in that the desired form can be created or that the required manufacturing speeds can be reached. Their other role within the company stems from their technical expertise. Through simulation and engineering understanding they are able to advise other departments on feasibility of their designs and working, or virtually simulate potential designs for pressure or fluid dynamic performance. Engineering design therefore also covers a broad spectrum of the design process ranging from original design (e.g. bespoke machinery) all the way through to drafting and preparation for production (e.g. tooling re-design and manufacturing instruction).

As will be presented in the following sections, some thoughts on quantity and type of design work were necessary when selecting participants. In addition to a requirement for a willingness to be recorded, a focus on actual design was needed throughout the recording procedure. In each department, designers played both a design role and project management role on a day-to-day basis. This project management element could be highly significant, with the designers intermittently spending a majority of their time on the organisation of testing procedures, customer meetings, marketing considerations, accounts, and many other responsibilities. As these time periods were not design-based, they were not part of the main focus of research.

The consequence of the split focus of the designers was in reduction of those who would prove viable and useful participants – a smaller proportion of designers could be described as completing design-based work in any single time period. The participants chosen were therefore selected on a combination of willingness to take part, and a focus at point of recording on design-based activities.

As within study two, there was a difference in experience of the designers. Both participant 4A and participant 4D were expert with 10 years' experience, while 4B and 4C were graduated (and hence experienced) but non-expert. The primary consequence of this is in analysis, as the behaviours of participants 4B and 4C can be said to represent industry, but certainly not expertise. Experience of the participants is given in Table 80.

Table 80: Experience of study three participants

	Participant 4A*	Participant 4B	Participant 4C	Participant 4D
Department	Innovations	Innovations	Innovations	Engineering Design
Experience	118 months	16 months	28 months	300 months

*Note that designers are named according to the convention within studies one and two, where the number denotes the study and the letter the participant. Usefully for analysis, Participants 4A, 4B and 4D were also participants 2N, 2O and 2P in the observation study respectively. This allows for further comparison of results.

10.3.3 Recording Process

The study process was designed to be unobtrusive to as high an extent as possible. Following briefing and the completion of a background questionnaire (shown in Appendix I), steps were taken to record the natural, individual working processes of each designer.

Following the procedure used within study two (see Section 7.4); the designers were recorded through a combination of screen capture software (Camtasia v8) and logbook recording (through Livescribe). The particular benefit of the use of Livescribe was as in study two – real-time capture of the written work of each designer.

Designers were instructed to record their work on a daily basis using the screen capture software. This was a simple, largely automatic process requiring only 10 seconds of designer input each day. The screen was captured in standard video format and recorded directly to an external storage device, which was collected, backed-up and replaced nightly. During recording, there were no indications on screen of the software running.

As Crown would only permit recording of projects that were not covered by an external Non-Disclosure Agreement (NDA) with one of their customers, the participants all had the option to pause recording at any point. This could, however, be detected in the video outputs.

Total recording times for each participant are as shown in Table 81.

Table 81: Recording details for Study Four

	Participant 4A	Participant 4B	Participant 4C	Participant 4D	Total
Recording days	7	9	11	9	36
Recording time	32hrs 37min	38hrs 39min	75hrs 3min	32hrs 45min	179hrs 5min

10.4 Project Context within Industry

During analysis, it was necessary for study three to be split into two discrete sections. As analysis began on the initial stages of data review, it was immediately clear that the behaviour of the designers was influenced by the purpose of their work within each project. To begin to understand this influence, some analysis of the scope of each project was needed as an initial step; both to identify comparable and relevant data, and to provide some understanding of the influence of project purpose. This section forms what is in essence a preliminary analysis of the project context of the industry designers at Crown, with behavioural analysis of industry designers presented in Section 10.5.

Even within design-based work, the scope of requirements for the designers differed significantly. For example, some cases demonstrated typical design work at some level of detail, in which the designer would produce a physical or virtual design based on a brief. In another case a designer would produce a virtual prototype of a design, but purely for the purpose of rendering an image for a customer presentation, or to produce marketing material.

The latter of these gave very little requirement for physical interpretation of the product (rather consideration of graphics that could be associated with it) and so the design work completed cannot truly be said to be of the engineering design domain. It can be classed as design of a form, but cannot be assumed to be comparable to design working within engineering, or within studies one and two.

This distinction is particularly important within this study. The variation in behaviour caused by the differences between study one, study two, and industry is a primary phenomenon of interest. It is therefore necessary in the first to perform some analysis of comparison of design context between studies one, two, and four, firstly to highlight comparable data, and second to inform findings.

Studies one and two both provide a realistic example of design in terms of process and domain. Study one required the participants to develop a brief into a working, proof-of-principle prototype, therefore involving a substantial proportion of the engineering design process. Study two was specifically designed to mimic the industry design process in a highly condensed form. Accordingly, the goal of contextual study was to identify projects within industry that also represented the generic engineering design process accurately, but were subject to the influences inherent in industry working.

10.4.1 Identifying Study Context

In essence, this process of comparison is an analysis of one contextual element of the design working of the industry designers. The purpose and output of a design project form one element of the domain in which it is completed. Particularly in engineering design, there is a highly solution-focused nature (Lawson, 2006), which is completed for the development of a physical product.

In cases in which the purpose of the design working is not for the development of a physical product, the process cannot be said to be contextually similar. This is a particularly important element of the thesis as a whole; as described in Chapter 2, the domain and context of analysis are an important constant that must be maintained. Also as described in Chapter 2, cases that fall outside of the scope of engineering design also fall outside of the primary research scope;

maintaining focus firmly on engineering design allows more detailed analysis, and negates the assumption that behaviour is independent from field or domain.

This analysis formed the first element of determining level of comparability between studies one, two, and four. A brief comparison of the context of the study was formed based on output and purpose of design, and factors thought to influence designer behaviour. As there is no known literature classification of the influencers on designer behaviour, individual categories have been derived; although in truth, a more complete method of systematically classifying context of a design situation would likely be a highly valuable tool in itself. The purpose of this analysis is therefore to allow comparison of the contextual elements that may influence the behaviour of the designers in industry and in studies one and two.

As it was the design process and individual differences of designers that form the phenomena of interest, differences within each are accounted for or studied directly within the framework and coding scheme that are used for analysis (e.g. designer approach and design stage). As such, the below presents only criteria outside of personal traits of the individual designer and process characteristics that may cause variation in behaviour.

Influencers of designer behaviour

As discussed in Chapter 4, a primary influencer is the domain in which the designer is working. This is clear through such examples as differing solution strategies of architects and engineers (Lawson, 2006), different personalities of people working within different fields (Feist, 1999), and the inability of experts from one domain to transfer their skills to another (Ericsson, 1996). It is therefore necessary to define the domain in which each project occurs. This was completed through interpretation of the purpose of the output of the design process; following the rather basic distinction of whether it was for the development of a product from some specific brief, or for some other reason. This categorisation therefore states only whether a design process falls into the umbrella of engineering or product design. Refinement could be made through analysis of the more specific domains to which it belongs, such as manufacturing design, machine design, or mechanism design. However, the focus of this thesis lies solely on design in the sense of production of a physical output within the context of engineering, looking at the general characterisations that can be made within. Such detailed analysis can be considered an extension for further work.

A second criterion of influence on the behaviour of designers is the time dimension under which they work. When under stricter time restrictions the performance and innovation of behaviour will increase, so long as that pressure is not significantly above that desired (Andrews and Farris, 1972); while a higher amount of time has also been shown to produce better results and inter-personal interaction (Kelly and McGrath, 1985). It follows that should the performance or output of processes under differing time conditions must change, and is likely a result of some change in the actual behaviour displayed.

Another important factor is that of the team in which the designer is working and its composition. Including variations in performance based on autonomy, leadership, size, and heterogeneity (Stewart, 2006, Guzzo and Dickson, 1996), the team to which the designer belongs plays a significant role in output. In addition, the individual characteristics of those within the team affect the team performance on the whole (Lepine et al., 1997, LePine, 2003). In this thesis, studies one and two involved the individual working of designers (as is required to study individual behaviour). To maintain realism, study three made no restrictions with regard to team working. The extent to which the study three participants worked within a team must therefore be considered in comparison of behaviour.

A further criterion is the physical environment in which the designer is working, which has also been shown to influence their behaviour (Davis, 1984, Harrison and Dourish, 1996). The effect of physical environment has been minimised within this thesis by allowing and encouraging designers to work within familiar surroundings, thus enabling them to work within an appropriate “place” (see Harrison and Dourish, 1996). It is still, however, a consideration for the context of the design that may influence the behaviour of the designers in industry.

These criteria form categories for analysis of each study, which will allow some understanding of the varying context to which they are subject. The following analysis considers these differences and the role that they play.

Process of contextual analysis

In order to determine the context of the working within recorded data it was first divided into the individual projects worked on by the participants. These could be easily deduced from the video as they were often linked to a projects database or brief from which the designer was working. Additionally, each project was typically quite different in focus or type, allowing easy determination of boundaries between each.

Next, study one, study two, and each participant project within study three was compared to the behaviour influencers described. This comparison is presented in Table 82.

Results of contextual analysis

The cohesion of studies one and two have been presented in Section 7.5. In essence, Table 82 forms an extension to this thinking in terms of design context, specifically relating to those projects in study three.

From the table, there are several projects that are not directly comparable to either study one or two. In particular, projects 1, 3 and 5 of participant 4A, and projects 11 and 15 of participant 4C. Those projects of participant 4A were instead concerned only with reviewing the current state of each, no evidence of any progression occurred; while those projects of designer 4C were related solely to marketing – the designer was required only to produce marketing images for existing products. It cannot be said therefore that these projects are of an engineering or product design domain as recorded in the data – the work of the designer was in no way concerned with the development of the product.

In terms of time restrictions, study two is different to both study one and study three. In near-all projects, including all those that are of the engineering domain, the designers were subject to unrestrictive time limits. Progression was expected, but firm dates for completion were not present. With the exception of study two, all data can therefore be said to be of comparable context in terms of time.

For the most part, team working within recording did not occur, although within study three it was not prohibited. Particularly for designers 4A and 4D, their experience granted them largely autonomous working, which they exercised in all recorded data. Examples of team working for these designers would typically include organised brainstorms or specific requests for information out of their personal experience, none of which occurred within the recording time frame. Both participants 4B and 4C, being of lower experience, were reliant on some input from their team throughout their projects, and so are perhaps less comparable to either studies one or two.

All were also highly comparable in terms of working environment, in the sense that all working environments were the typical setting of the designer. Clearly, there are individual differences between each; examples of creative spaces demonstrate the difference that can be caused purely by surroundings (McCoy and Evans, 2002). Unfortunately, however, these considerations form a broad research topic that is towards the edge of scope of the primary research aim within this work. They are therefore considered a limitation of study, and an opportunity for further work.

In all, many of the projects within study three present similar context to those in studies one and two, and to engineering design in general. Due to their realistic design situation, they therefore serve as suitable examples of designer behaviour in their own right, and a valuable counterpoint to develop understanding of the impact of industry context on designer behaviour in comparison to studies one and two.

10.4.2 Design Stage

Also evident at the initial review of recorded data was the variance in design stage and activities that the designers were completing. Although all lying within the design process as typically understood to exist, it was the activities that typically lay within later-stage design that are of particular interest in this thesis.

As a result, there was a need to form a preliminary understanding of the design activities that each project involved, in order to identify suitable candidates for more detailed analysis. This was completed through coding for the activities proposed by Hales (1986)(see Figure 44), which in turn are based on the model of Pahl and Beitz (1984). These activities are not tied to detailed analysis of behaviour and are based on a chronological interpretation of the design process (see Section 3.3), and so cannot be used for more detailed coding. They therefore give a good, if not detailed, indication the general work that the designer was completing in each project, and hence can form a basis for comparison.

The process of determining each activity of the designers was completed through careful, manual study of the videos. Each was played at a two and a half times actual speed, and was coded according to the activities of Hales. This process was used to indicate the occurrence of an activity and not the frequency of occurrence or length of occurrence, as its purpose was only in indication of general design stage of each project.

The results from this analysis are presented in Table 83. Note that not all activities of Hales occurred, and only those that did are included in the table. Also note that the lowest two activities, "XI – Information retrieval", and "XR – Information reporting", are not inherently included in any design stage, rather appearing throughout the design process.

Results of design stage analysis

As can be interpreted from Table 83, there are several projects of particular interest in study three. For participant 4A, project 4 is of the engineering design domain and includes a large proportion of the design process, particularly typical later-stage activities.

Table 82: Context of each design project

Participant	Project	Output type	Output Purpose	Time restriction	Team working	Environment
Study 1		Physical prototype	Design development	Present, but minimal	Unrestricted, but not encouraged	Participant choice – familiar
Study 2		Design schematics	Study requirement	Strict	None	Standard environment
Participant 4A	1	None	Review	None	None	Standard environment
	2	Proposal presentation	Customer proposal	Present, but minimal	None	Standard environment
	3	None	Review	None	None	Standard environment
	4	Physical prototype	Product demonstration	Present, but minimal	None	Standard environment
	5	None	Review	None	None	Standard environment
	6	Proposal presentation	Customer proposal	Present, but minimal	None	Standard environment
Participant 4B	7	Virtual prototype/simulation	Design development	Present, but minimal	When required	Standard environment
	8	Project brief	Design development	Present, but minimal	When required	Standard environment
	9	Virtual prototype/simulation	Design development	Present, but minimal	When required	Standard environment
Participant 4C	10	Review presentation	Reporting	None	None	Standard environment
	11	Image	Marketing materials	Strict	When required	Standard environment
	12	Virtual prototype/simulation	Design development	Present, but minimal	When required	Standard environment
	13	Project brief	Design development	None	When required	Standard environment
	14	Concept variants	Design development	Present	When required	Standard environment
	15	Image	Marketing materials	Strict	Delegated	Standard environment
Participant 4D	16	Technical drawing	Part production	Present, but minimal	None	Standard environment
	17	Technical drawing	Part production	Present, but minimal	None	Standard environment
	18	Technical drawing	Design development	Present, but minimal	None	Standard environment

Table 83: Appearance within study of the design activities of (Hales, 1986). Light grey indicates the occurrence of an activity within the project, dark grey indicates that the project is invalid.

Activity	Participant 4A						Participant 4B			Participant 4C						Participant 4D		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
PP – Product planning																		
CP – Clarifying problem																		
SP – Specification preparation																		
CV – Concept variants																		
EV – Evaluation of variants																		
ML – Main layouts																		
SS – Search for solutions																		
DL – Detailed layouts																		
CL – Check layouts																		
EL – Evaluate layouts																		
RD – Review design																		
PD – Prepare documents																		
FD – Finish drawings																		
XI – Information retrieval																		
XR – Reporting/reviewing																		

For participant 4B, there is a prominent focus on early stage design. They do, however, show some progression through stages of the design process within their projects, and some examples of physical concept development. Both projects 7 and 9 are equal examples of this.

For Participant 4C, there was a wide variation in activity design stage, although the designer remained fairly focused within each project. In reality, the sporadic nature of working and lack of later-stage design make their projects of lower suitability for comparison.

Participant 4D is of particular interest, being both the most experienced designer, and demonstrating the strongest focus on later-stage design. Their projects primarily concerned physical component and machine design, followed by drafting and manufacturing instructions.

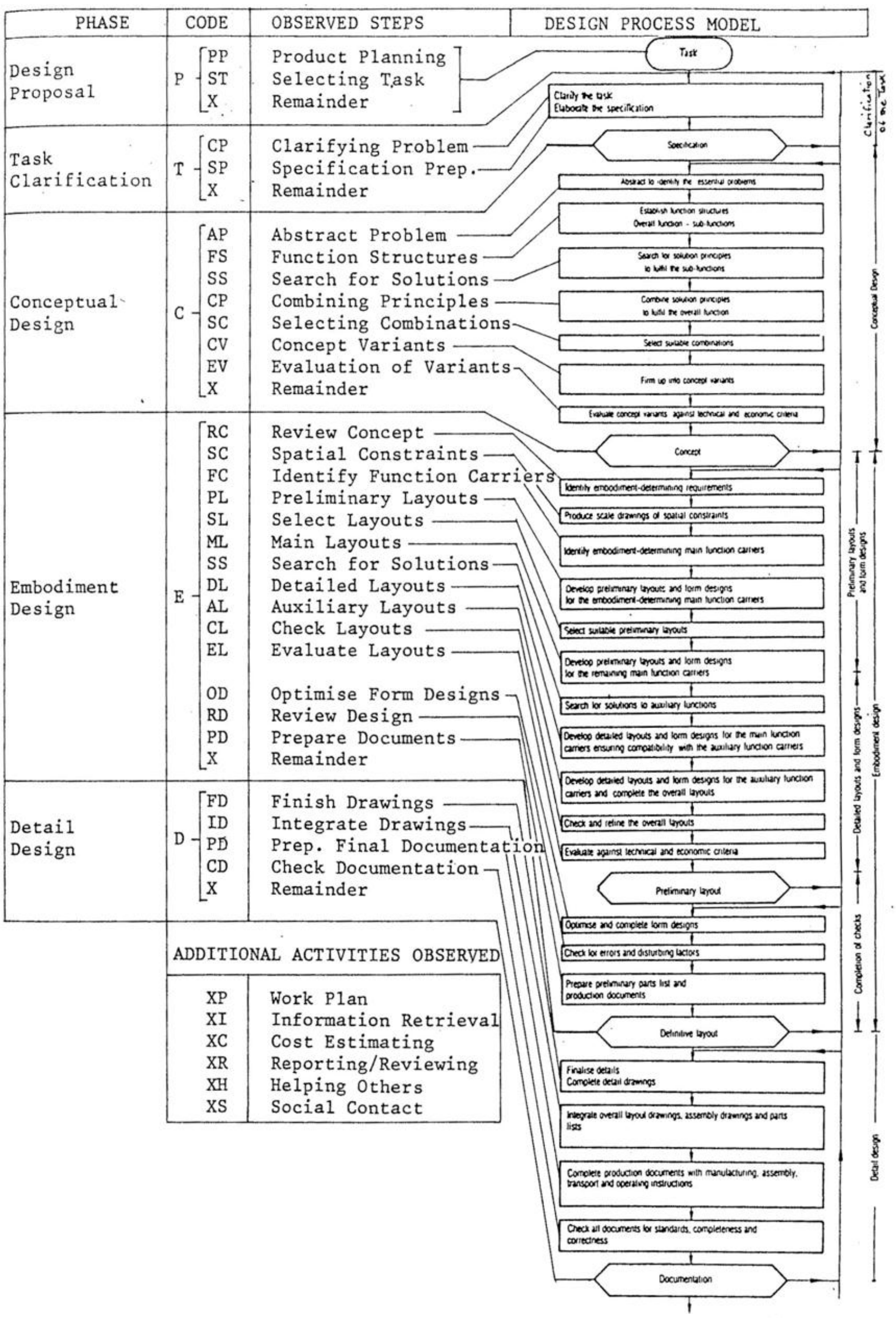


Figure 44: The design process activities of Hales (1986)

10.4.3 Summary: Contextual Analysis of Industry

This section has presented some contextual details of study three, an observational study completed in industry. During the initial stages of analysis of data from study three, the observation was made that elements of project context were influencing the behaviour of the designers. The influence needed some description – firstly to understand its role in manipulating the industry design process, and second to understand the extent to which results from studies one and two can be considered comparable to industry design.

These goals have been met through a contextual analysis of each study, and the projects completed by the designers within study three. In actuality, the majority of study three is comparable to studies one and two in terms of domain, working conditions, and working environment. Differences in behaviour between these comparable projects and studies one and two are more likely a result of individual designer than purely situational factors. Differences due to design stage and activity are more significant, with designers from the innovations department of Crown tending towards early stage design. Many of their projects are therefore less suitable for more detailed analysis and comparison.

By understanding such differences in context that do exist, a more detailed understanding of designer behaviour in industry can be formed. This purpose forms the following section presented within this chapter. Through the contextual analysis, project 4 of designer 4A, projects 7 and 9 of designer 4B, and all projects of designer 4D, were identified as comparable to studies one and two. All are of the engineering design domain, all involve some element of later-stage type activity, and all show progression through the design process. It is therefore these projects that form the primary set for more detailed analysis. These studies are then also the best candidates for more detailed behavioural analysis.

10.5 Study Four – Design Behaviour in Industry

It is from this point that the final part of analysis within this thesis can occur, studying the actual behaviour of designers working within industry on realistic projects. From this analysis it is possible to provide further detail and understanding of the findings demonstrated by studies one and two, and also to provide significant direction for further work.

10.5.1 Selection of Data for Analysis

From the contextual analysis, there are six projects of higher interest; projects 4, 7, 9, 16, 17, and 18. Of these, projects 4, 7, and 17 presented a clear majority in quantity of recorded data, as they were the primary design projects of each participant at the time. For this reason, projects 4, 7 and 17 were those studied in more detail. A brief description of each is provided in Table 84.

An additional benefit of the choice of these projects is that each was worked on by a different designer, each of whom also took part in study two. They therefore allow more direct analysis of results across studies.

Table 84: Description of projects studied in detail in study three

Project	Participant		Description
	Study 4	Study 2	
4	4A	2N	Finishing and finalising the design of a plastic tub (2 sizes) and lid (identical), to be sent for rapid prototype. Required to be fully-functional look-a-like models for customer review.
7	4B	2O	Designing several profiles for a section of common metal packaging that requires high pressure performance. Based on recent developments, there was a belief that extreme improvement in performance could be achieved.
17	4D	2P	Re-design of a punch assembly with alternate diameter punch. The punch is a machine of some complexity, with much potential for propagation of changes throughout the system.

10.5.2 Coding Process of Study Four

The actual coding process within study three was very similar to that within study two, in that it was based off of the screen capture of the designers and from their logbooks. The coding procedure therefore remained much the same.

As part of the analysis within Section 10.4, the parts of data that related to each project had already been identified. A sample containing each day in which the majority of the designers' time had concerned the chosen project was taken, and coded in detail. Quantity of coded data is given in Table 85.

Coding itself took place first by transcribing each video. The actions of the designer and entities appearing in their work were described on a minute-by-minute basis. These were then analysed in detail in order to interpret the tasks that the designers completed, their types, and any evidence of creative behaviour. Following transcription, the coding process took place in a single sitting for each participant, across their data, in order to maintain consistency of interpretation.

Table 85: Summary data for study three behavioural analysis

Participant	Length of data	Total number of tasks	Later-stage type tasks
4A/2N	12hrs 51min	20	20
4B/2O	9hrs 46min	13	12
4D/2P	10hrs 29min	24	24

Each recorded video also contained some examples of non-applicable data in the form of general administration – time bookings, scheduling, and unrelated emails. As all email content was recorded as part of the study procedure, each could be judged in detail as related to a project, or not. All non-applicable data was excluded from analysis.

As data for analysis was selected following analysis of activities, there was a low proportion concerned with early-stage design rather than later-stage. However, in keeping with the rest of the thesis, only later-stage type tasks were included in analysis.

10.5.3 Results of Industry Observation

There are two possible streams to analysis of this data; first as findings representative of industry working behaviour, and second as in comparison to the results of studies one and two. For the former of these, although the results can provide direction, there is too small a sample for fully representative interpretation. The second is therefore the better option; results from data can be used to describe industry working behaviour, in contrast to non-industry working behaviour of studies one and two. As analysis of some contextual influencers has already been carried out and participants are consistent between studies two and four, there is suitable information to make measured comparison.

Following the headings of analysis within Chapters Eight and Nine, Table 86 and Table 87 present the proportions of different task types of each design in study three. The first of these gives results specific to the designers, allowing observation of how their behaviour varied specifically between the two cases. Table 87 gives a comparison of study three to studies one and two in terms of how different each study three participant was to the group average in the others.

Table 86: Comparison between observation (Study two) and Study four results

Category	Participant 4A/2N (%)		Participant 4B/2O (%)		Participant 4D/2P (%)	
	Study 2	**Study 4**	**Study 2**	**Study 4**	**Study 2**	**Study 4**
Application-type tasks	94.4	70.6	100	75.0	84.6	62.5
Information-type tasks	5.56	29.4	0.00	25.0	15.38	37.5
Within-entity type tasks	66.7	41.2	70.0	58.3	69.2	37.5
Cross-entity type tasks	33.3	58.8	30.0	41.7	30.8	62.5
General expansive-type tasks	44.4	8.33	20.0	33.3	30.8	16.7
General restrained-type tasks	55.6	94.1	80.0	66.7	69.2	83.3
Effectuating-type task proportion	41.2	8.33	20.0	33.3	36.4	26.7
Astute-type task proportion	100	0.00	0.00	33.3	0.00	0.00
Within-entity expansive task proportion	33.3	14.3	0.00	28.6	22.2	0.00
Cross-entity expansive task proportion	66.7	0.00	66.7	40.0	50.0	26.7

The appearance of creative behaviour

Within study two designers demonstrated an occurrence of creative behaviour between 20% and 44.4% (general expansive-type tasks; Table 86). These proportions were not maintained into study three, with both participants 4A and 4D dropping in proportion (44.4% to 8.33%, participant 4A; 30.8% to 16.7%, design 4D; Table 86), and participant 4B raising their proportion (20.0% to 33.3%). This change demonstrates quite different creative behaviour occurring in the two studies.

There is a clear reason for this when considering the purpose of the projects completed in each case. Study two required the designers to produce a detailed design for a specific system, based on a given brief. They were free to proceed as they wished without any expectations; either a more creative or more non-creative process were viable alternatives. The projects within study three were slightly different in nature.

Project 4 required the designer to finalise a design for prototyping. Their brief primarily concerned checking dimensions were suitable for the manufacturing method and altering if not, along with some other small alterations; ensuring functional capability; and the design of any small functions that were yet to be included (in this case, the "click" mechanism on closing the lid). As a result, there was little work involved that required manipulation of the design beyond matching the requirements of the manufacturing method.

Project 7 involved the design of a profile for a common part of metal packaging that demonstrated significantly improved pressure performance. As part of this process, the designer was expected to produce many different profiles, all of which would then be tested by the simulation team for performance. Their project then inherently required exploration – hence creative behaviour – in order to proceed; creative behaviour needed to occur independent of the designer's behavioural preferences.

Project 17 involved a substantial re-design of a machine tool assembly. There was scope within this process for the designer to make several design decisions according to their preference and experience – their only requirement was that the finished re-design be capable of accepting new tooling. The work was, however, highly detailed and with a primary focus on structure. There was little consideration of how the system would work or behave, and rather the new structural forms that current components must take. This approach was necessary in order to maintain compatibility with other machinery.

There are then potential reasons for the difference in occurrence of creative behaviour. The creative proportion of participant 4A dropped significantly as there was little scope for change in project 4, beyond matching dimensions to requirements. Potential exploration was severely limited by their brief. The creative proportion of participant 4B grew as project 7 required creative behaviour to proceed; the designer had no choice. The creative proportion of participant 4D dropped by a smaller amount because of the highly detailed focus of their tasks (which finding five demonstrated as typically less-creative), although they were not directly limited by project scope.

These results therefore demonstrate the importance of considering the actual project on which a designer is working when studying their behaviour. Study two presented a rather neutral case, designed to mimic a complete design process across its entire procedure. It was also neutral in its expectation of designer creativity. The projects in study three were not the same in this regard. The expectation and opportunity for creative behaviour varied greatly between each; a condition evident in the resultant behaviour of each designer. There results therefore present the finding that:

Twenty-Six: *The individual expectation within a project will alter the appearance of creative behaviour of a designer in industry.*

Note that finding twenty-six is considered a confirming finding, in that it agrees with current expectation within the field.

Task-type by output

An area of closer consistency between the behaviour of the participants in studies two and four is in their task focus throughout the recorded process. In each case, a focus on application-type tasks within the later-stages of design remained. The proportions did vary however; all designers completed more information-type tasks than in study two alone, although still less than the group average in study one Table 87. Within this thesis, the potential for task-type to be situation dependent in terms of time has been proposed, where severe time restriction encouraged quick progress through a focus on application-type tasks. Were this the case, the lower (but still majority) proportion of application-type tasks would agree; the designers in study three were of similar time restriction to study one. Additionally, the increase in application-type task focus between study one and study three specifically has been supported in finding twenty-three, which demonstrated that more experienced designers have a higher application-type tasks focus.

The primary finding here therefore agrees with several findings, relating to the pattern of an application-type task majority in late-stage design. The potential relationship to time is interesting however, and further discussed in Section 11.5.

Task-type by transformation

In relation to the focus on within-entity and cross-entity type tasks displayed by each designer, the results of study three demonstrate a consistently lower focus on the within-entity type than study two (41.2% rather than 66.7%, participant 4A; 58.3% rather than 70.0%, participant 4B; 37.5% rather than 69.2%, participant 4D; Table 86). These lower values in study three are in reality far closer to the results of study one (4.30% difference, participant 4A; 12.9% difference participant 4B; 7.97% difference, participant 4D; Table 87).

This discrepancy lends further support to proposals made regarding the influence of the design situation. Due to the restrictive design situation of study two, the designers completed a higher proportion of within-entity type tasks. When under fewer restrictions, the proportion of cross-entity type tasks increases. As a result, study two presented a high proportion of within-entity type tasks (that was consistent between experts and non-experts), while study three presented a proportion of similar scale to study one.

Creative approaches by output

Finding twenty-three states that expert designers consistently follow an effectuating approach rather than an astute approach, although this is hardly surprising given the predominance of application-type tasks in the studied stage.

Participant 4D, both most experienced and completing a project most similar to the other studies, also demonstrated a strictly effectuating approach. Designer 4A did according to the data, but this must be tempered with the very small occurrence of creative tasks. Designer 4B followed a balanced approach, but is not an expert, rather a non-expert working in industry. Accordingly, the data does not provide sufficient detail to give more than a suggestion of support.

As they are a subset of the occurrence of creative behaviour, the appearance of a creative approach is more closely tied to the results and discussion within Chapter 8. In the case of designer 4B, there was a requirement to complete expansive behaviour. It is then unsurprising that they demonstrated an increase in each approach in study three (+11.9% against effectuating, +11.5% against astute; Table 87). For designer 4A, the lower scope for creative behaviour makes it equally unsurprising that their creative proportion dropped (-13.4% effectuating, -21.9% astute; Table 87). Due to the more comparable design situation of project 17, but high focus on application type tasks, it is not surprising that their proportion of effectuating-type tasks remained similar, but proportion of astute-type tasks dropped (+4.93% effectuating, -21.9% astute; Table 87).

Table 87: Comparison between study three participants and group average of studies one and two

Category	**Participant 4A/2N (%)**		**Participant 4B/2O (%)**		**Participant 4D/2P (%)**		**Study 4 average***			
	Study 1	**Study 2**	**Study 1**	**Study 2**	**Study 1**	**Study 2**	**Study 1***	**S.D.**	**Study 2***	**S.D.**
Application-type tasks	9.7	-12.8	14.1	-8.42	1.61	-20.9	8.48	5.18	14.1	5.18
Information-type tasks	-9.7	12.8	-14.1	8.42	-1.61	20.9	8.48	5.18	14.1	5.18
Within-entity type tasks	-4.3	-25.7	12.9	-8.51	-7.97	-29.3	8.38	9.08	21.2	9.08
Cross-entity type tasks	4.3	25.7	-12.9	8.51	7.97	29.3	8.38	9.08	21.2	9.08
General expansive-type tasks	-23.6	-15.9	3.85	11.6	-12.8	-5.09	13.4	11.3	10.9	11.3
General restrained-type tasks	23.6	15.9	-3.85	-11.6	12.8	5.09	13.4	11.3	10.9	11.3
Effectuating-type task proportion	-24.9	-13.4	0.11	11.9	-6.56	4.93	10.5	10.6	9.98	10.6
Astute-type task proportion	-23.7	-21.9	9.69	11.5	-23.7	-21.9	19	15.7	18.4	15.7
Within-entity expansive task proportion	-6.05	1.11	8.23	15.4	-20.3	-13.2	11.5	11.7	9.89	11.7
Cross-entity expansive task proportion	-37.1	-39.1	2.9	0.938	-10.4	-12.4	16.8	16.6	17.5	16.6
						Average	**11.8**	**10.6**	**14.8**	**10.6**

*Averages are for absolute values of differences, not values as shown.

What the comments made within this section suggest, is the importance of studying project context when determining designer behaviour. As demonstrated in Chapters Eight and Nine, when in identical design situations, the behaviour of designers will vary according to personal approach and experience. There are implications for this in several areas. However, as shown by the results within this chapter, and suggested throughout this thesis, it is equally vital to consider the individual design situation and context. When this is understood, the individual styles of the designer can be supported; but the role of project context must also be considered.

Creative approaches by transformation type

One area in which there is strong consistency between all studies is the pattern of creative behaviour occurring within cross-entity type tasks, rather than within-entity type. In each study, a majority of participants have demonstrated a higher proportion of the occurrence of creative behaviour in cross-entity tasks. This therefore remains a particular trait of designer behaviour as understood within this work (and stated in Finding Six), and presents a strong potential direction for creativity research.

10.6 Summary: Design Context

This chapter has presented results in two discrete sections, both aimed towards providing understanding of the results within Chapters Eight and Nine in a more realistic light. This has been initially through a comparison of results of non-experts with those of experts in an identical design situation, and finally through discrete study of experts in a realistic design situation. Due to the more descriptive nature of study, only one conclusive finding is given from the study of designer behaviour in industry; shown in Table 88.

Table 88: Findings related to contextual analysis of designer behaviour

Finding Number	Finding
26	*The individual expectation within a project will alter the appearance of creative behaviour of a designer in industry.*

Through these methods, this chapter presents the results that allow deeper understanding and qualification of the results of Chapters Eight and Nine. Although valid in and of themselves, for findings to be of relevance and use to industry there must be a specific understanding of the influences and differences that occur in an industry setting. Particularly according to the views within this work, there is inherent difference in designer behaviour due to the stage of the design process at which the designer is working, and hence due to the design situation.

This chapter then presents both points for discussion and directions for future work, through highlighting influencing factors in the designer and their working context, and the variation in behaviour that results.

The conclusion of this chapter marks the conclusion of presentation of results within this thesis. Through the completion of four individual studies, Chapters Eight, Nine and Ten have considered the appearance and style of creative behaviour within late-stage design, the comparison of late-stage behaviour with early, the effect of behaviour on output quality, and the influences on behaviour of the wider industry context. In total, twenty-six findings have been formally recorded, which are discussed in detail in Chapter 11.

Chapter 11: Overall Discussion

The purpose of this chapter is to present discussion of the findings formalised through Chapters Seven, Eight and Nine. Through comparison between the situations of each observational study and assessment of quality, deeper understanding creative behaviour within later-stage design can be formed.

In this way this chapter forms the discussion that addresses the research aim presented in Chapter 5, and forms the final section of the thesis as presented in the thesis structure (Table 13).

Discussion of results is formed through the categories of analysis presented throughout each results chapter, and concerns the types of tasks designers employ within later-stage design, their creative behaviour, the quality of their output, and the role of industry context. Following, the chapter presents the formalised characterisations of designer behaviour within later-stage design that the results of this thesis allow and some of the potential implications for support.

11.1 Introduction - Study through Tasks

Within engineering literature, the design process is presented in one of two ways; either as a prescriptive series of steps (see Pahl and Beitz, 1984, Pugh, 1990), or as a descriptive understanding based on the study of designers (Cross, 2000). As discussed in Section 3.5, these two methods have a different purpose within the greater field; a prescriptive model aims to provide guidance to designers while working, and a descriptive model aims to provide information and understanding that can be used to build theory (Ullman et al., 1988a). It is only with such knowledge gained from descriptive understanding that more progressive steps can be made, such as the provision of methods of design process support and enhancement.

Clear within many engineering process models is the focus on activities as defined within Activity Theory (AT – see Section 3.2) (see Kaptelinin et al., 1995, Redmiles, 2002). With steps focused on the goals within the process that designers must achieve (see Pahl and Beitz, 1984, Hales, 1986), process models aim to describe design through an abstracted viewpoint, away from the designer and the product under development. While this brings broad applicability to each model, it also abstracts away from the actual process of the designers, those individual actions that they complete within an activity, and so gives little guidance to their individual behaviour. As understanding of behaviour forms the earlier step in the formation of design models, it is the study of designers directly that must be completed when extension to theory is necessary. To this end, this thesis has aimed at the direct study of designers' behaviour, through their individual tasks.

As within AT, this places a distinction between activity and task (termed *activity* and *action* within AT), but even then does not reach the extent of what is necessary for complete understanding. The tasks of the designer describe their behaviour, but these are performed through sub-tasks, a hierarchical structure that runs down to the cognitive level (Kaptelinin et al., 1995). There are therefore multiple levels of descriptive understanding that can be formed – the tasks that a designer completes, followed by the cognitive processes that they use to complete them.

It is at this junction that literature branches, with different researchers focusing more singularly on either the behaviour of a designer, or on their cognitive processes within design. While there is clear overlap between these two subjects, this thesis takes a rather pragmatic view in its study; when describing that which has not been previously characterised, it is first necessary to understand *what* designers do, before one can understand *how* they do it.

From the identification of a particular gap in knowledge (see Section 4.5), this thesis takes particular interest in the later-stage design process behaviour of engineering designers. To achieve this, understanding from the research field of creativity is employed; providing structure on ways in which creative products and behaviour can be interpreted, how they emerge, and their outcomes.

Given the trends of the field, understanding gained from this thesis could be implemented into process model based understanding, tools and support methods, managerial methods, and design education. Through detailed knowledge of later-stage design behaviour, detailed improvements can be suggested and made.

11.2 New Findings and Confirming Findings

As introduced in Chapter 8, findings within this thesis can be described as either an addition to knowledge according to the gap presented in chapter 4, or as confirming understanding as found within existing literature. Findings within both are found throughout the results chapters and pertain to a variety of subjects, both acting to increase understanding in the wider field and increase confidence in the validity of the work that has been performed. Throughout Chapter 11, both sets of findings are drawn upon in detailed discussion; the confirming findings acting as support for the understanding gained from new findings, and both aiding in addressing the knowledge gap identified in Chapter 4.

Table 89 and Table 90 overview the findings that demonstrate new and confirmed knowledge and their importance.

Table 89: FIndings that confirm existing understanding

Finding Number	New / Confirmed Finding	Finding
1	Confirmed	*Within the design process as a whole, creative behaviour is in a minority to non-creative behaviour.*
2	Confirmed	*Different designers will display varying quantities and forms of creative behaviour, whether completing different projects (as in study one) or the same (as in study two).*
5	Confirmed	*Later-stage design typically contains less creative behaviour than early-stage design.*
11	Confirmed	*Through the stages of design, there is a general shift in focus from information-type tasks to application-type tasks*.
12	Confirmed	*Within later-stages, designers generally concentrate on non-creative methods of behaviour and structural development of the design.*
15	Confirmed	*During later-stage design, creative behaviour primarily concerns the determination of system behaviour and preliminary structure.*
17	Confirmed	*Despite preference for one over the other, a designer's creative approach can vary through the design process. Some designers remain astute in later-stage design, while others become effectuating.*
19	Confirmed	*In the same design situation, the design solutions of experts are often better than non-experts, both according to metric-based assessment and expert judgement.*
20	Confirmed	*By the assessment of an experienced human observer, when based against the definition of creative products, expert designers will produce a more creative solution than non-experts in an identical design situation.*
26	Confirmed	*The individual expectation within a project will alter the appearance of creative behaviour of a designer in industry.*

In general, these confirming findings relate to results that are separate to the core concepts and focus of the coding scheme; those that do not consider creative approaches, or specific types of task (and subsequently behaviour). They can be related to known understanding in the field, either agreeing with research, or demonstrating expected patterns that have been discussed in literature.

Findings one and two concern the appearance of creative behaviour within the general design process. Given prior expectation of later-stages of design being less creative than early, and the known variation in personal traits leading to varying creative (see Chapter 2), this is not unexpected. It does however demonstrate validity in the coding scheme that such expected results are demonstrated.

Findings five, eleven, twelve, fifteen and seventeen relate to designer behaviour through the design process, particularly in terms of stage difference. Particularly in terms of those relating to focus of later-stage design as opposed to early, findings agree with a wide body of work on subject of design stages (Pahl and Beitz, 1984, Pugh, 1990, Ullman, 1997, Cross, 2000). The significant benefit in this work, however, is in the demonstration of difference in design situation between early design stages and late, which have significant potential to alter the behaviour of the designer. It should be noted that finding seventeen is confirmatory in that creative behaviour is understood to vary throughout the design process, but new in that the changes according to each creative approach are not previously recognised in literature. Findings five and seventeen mirror findings one and two, but with a design-stage specificity; as according to common expectation and understanding within the field, later-stage design contains less occurrence of creative behaviour than early, and designers creative behaviour has potential to vary according to situation.

Findings nineteen and twenty concern expert behaviour and the oft-made assumption that their behaviour reflects “better” practice within the field. These findings act both to provide evidence of this assumption, and to provide validation of the assessment methods used to judge quality and creative products within this work. The particular value of these findings in this work is in confirmation of the validity of comparison between experts and non-experts, as a basis for identifying “better” practice within design behaviours.

Finally, finding twenty-six demonstrates the well-recognised context-sensitivity that permeates engineering industry, and the varying situation in which engineers must work. As is a fundamental premise of this thesis, the engineering situation varies throughout the design process due to situational influences, process influences, and a change in subject. It then follows by expectation that design behaviour will vary dependent on the type of behaviour that is necessary or appropriate given the design situation. This is a useful finding in its highlight of the importance of context sensitivity in the study and understanding of engineering design.

Each of these findings is discussed in more detail throughout Chapter 11 according to their subject and in tandem with the new findings to which they relate.

Table 90 lists findings within this thesis that provide new understanding. In their majority, they relate to findings that can be formed and understood only through the framework and coding scheme presented in Chapter 6. Each of these findings is discussed in detail in the following sections, using confirming findings for validation and support, as well as to inform interpretation.

Table 90: Findings that form new understanding

Finding Number	New / Confirmed Finding	Finding
3	New	*Different designers will display different creative approaches within later stages of the design process, even when completing identical projects.*
4	New	*Creative behaviour within later design stages correlates significantly with creative style.*
6	New	*Designers more frequently display creative behaviour when completing cross-entity tasks.*
7	New	*The proportion of within-entity tasks to cross-entity tasks is in part indicative of the design situation and process streamlining.*
8	New	*Creative level is related to the proportion of tasks completed in an astute manner.*
9	New	*In a time-dependent situation, design quality is related to a higher number of discrete tasks completed by a designer.*
10	New	*Design quality, as judged by experts, is related to a focus on application type tasks, and a higher frequency of occurrence of creative behaviour.*
13	New	*Cross-entity type tasks are consistently creative throughout the entirety of the design process; in a minority during early-stage design, and a majority during later-stage design, when compared to within-entity type tasks.*
14	New	*More creative designers typically follow an effectuating approach during later-stage design processes.*
16	New	*A higher proportion of creative behaviour occurs in application-type tasks through both concept and embodiment design.*
18	New	*By expert judgement, high quality is more dependent on later-stage creative behaviour (correlations 4 and 5; Table 68), a late-stage focus on application-type tasks (correlation 3), and an early-stage focus on creative information-type tasks (correlation 1).*
21	New	*Experts demonstrate creative behaviour in their tasks, with a potential higher proportion to non-experts.*
22	New	*Experts have a near complete focus on application-type tasks in later-stage design.*
23	New	*Experts consistently follow an effectuating approach in later-stage design, suggesting superiority or higher approach suitability.*
24	New	*Experts are more often creative in cross-entity type tasks, to a higher proportion than non-experts.*
25	New	*Better design behaviour can be characterised by a majority proportion of creative cross-entity tasks.*

11.3 The Task-Based Design Process

Several findings within Chapter 9 concern the task behaviour of designers in general throughout the design process, with a particular (but not total) focus on later-stage design.

These findings allow understanding at the most basic of distinctions between types of task as defined in the framework and coding scheme, and so are presented first (see Table 91).

Table 91: Findings relating to basic task types

Number	Section	Finding
11	Chap 8	Through the stages of design, there is a shift in focus from information-type tasks to application-type tasks.
17	Chap 8	Despite preference for one over the other, a designer's creative approach can vary through the design process. Some designers remain astute in later-stage design, while others become effectuating.
22	Chap 9	Experts have a near complete focus on application-type tasks in later-stage design.

11.3.1 Information and Application Focus

Finding eleven presents a common-sense understanding of the design process, one that is implied in many design process models (see Ullman et al., 1988b, Pahl and Beitz, 1984, Pugh, 1990). As the design process continues, there is a switch in majority from tasks with an information-type output to tasks with an application-type output. In more tangible terms, this would be a variance from research and evaluation tasks, such as market analysis and technological research, to tasks concerned with the actual development of the design, such as layout design, configuration, and dimensioning.

There is a clear layer of necessity to this pattern. By their very nature the early stages of design are at a more primitive state than the late stages – there is little by way of a design product to consider. As such, much time is spent researching the possible requirements to include and designs that could be implemented, in order to make informed and effective design decisions. As the design process continues and the product begins to take shape, there is both option and need to focus on how it is put together, how it performs, and how it is made; all of which concern physical product rather than the knowledge and variables used for its production. This information-type to application-type drift is therefore a fundamental part of the design process and represents the necessity and purpose of the design stages.

A strong parallel can therefore be drawn between the identified task behaviour of designers within this work and the process activities of design models. An implied transition from information development to application development occurs in many; such as that of Hales (1986) and Pahl and Beitz (1984) (see Table 92). That the research completed within the thesis has empirically identified such widely-accepted theory is a boon to its validity.

The implication of these findings is therefore not in contribution to knowledge, but rather in added understanding and confirmation of the framework and coding scheme. As is to be expected given current literature, the actual behaviour of designers within later-stage design shows a concentration on development of application rather than information. As a result, for the purpose of support and enhancement of later-stage design practice, there is a clear approach to take. To be applicable to later-stage design behaviour, there is a need to focus on the support and enhancement of application-type tasks.

Table 92: Typical output of process activities

Hales (1986)	Pahl and Beitz (1984)	Typical Output Type
Early Stage Activities		
Product planning	N/A	Information
Clarifying problem	Clarify the task	Information
Specification Preparation	Elaborate the specification	Information
Later Stage Activities		
Detailed Layouts	Develop detailed layouts and form designs	Application
Optimise form designs	Optimise and complete form designs	Application
Finish drawings	Finalise details, complete design drawings	Application

Looking more specifically at finding twenty-two adds to this conclusion. Experts displayed a higher concentration of application-type tasks than non-experts within an identical design situation. There then arises a question of the impact of altering a designers information-type and application-type behaviour within their personal design process. Taking the characteristics of experts as an example of better design practice, it could be suggested that this reflects a more effective solution strategy and that non-experts should also focus on application-type tasks in their process.

As has been noted in the Function-Behaviour-Structure model of design of Sosa and Gero (2003), Gero (1990), the later-stages of design are therefore concerned with a conversation between system behaviour and system structure. Again, that this pattern is empirically derived by the framework and coding scheme provides support for its methodology and validity, but also provides some implications for further work. A strong focus on both of these areas is represented by a high application-type task focus, as seen in the processes of expert designers. Encouraging and enhancing the iterative process of focus between system behaviour and system structure in later-stage design may then prove an effective process of support and process enhancement.

In reality however, the implication is likely more subtle. Experts and non-experts are not of actual differing capability in the output of their process (Simon and Chase, 1973); the difference lies in their past knowledge and experience of similar design situations and suitable solution principles, and the ability to utilise effective solution strategy. Being more focused on application-type tasks than information-type tasks can therefore be seen as either an improved approach to take, or a result of the expert designer having a better "store" of past experience from which to draw. By consistently evaluating and the ability to utilise multiple streams of thought simultaneously (both traits of expert design behaviour (Ahmed et al., 2003, Seitamaa-Hakkarainen and Hakkarainen, 2001, Kavakli and Gero, 2002), the expert designer may remove the need for explicit information-type tasks to the same extent as the non-expert, thereby following the path-of-least-resistance (Ward, 1994, Moreau and Dahl, 2005) and greatly streamlining their process. These thoughts are supported by the fall from expertise when a designer works within a different field; when the information store is not available to them, they are unable to follow the more effective solution strategies.

The implication therefore becomes one of directions for further research. Experts perform fewer information-type tasks in later-stage design than non-experts. One part of this is due to necessity, but the other is due to their experience removing the need for information-type tasks to occur. Would it then be beneficial for this trait to be transferred to the process of non-experts, and if so, how could a higher application-focus be achieved? It is certainly not possible to instil expertise directly, it takes many years for expert performance to be achieved (Ericsson, 1996). It is also likely beneficial that the non-expert discovers and understands the information store of the expert personally, rather than procedurally following set guidelines. What can be achieved is the provision of information along the thinking of experts; supporting non-experts within those tasks that experts exclude. By improving the information-gathering process of the non-expert without preventing its occurrence, they will have opportunity to spend more time on application-type tasks, and potentially improve quality of output.

11.3.2 Variation between Stages of Design

Findings eleven and seventeen claim a difference in behaviour between early and late stage design. This is manifest in several different ways, including task-type and patterns within creative behaviour (see Sections 8.3 and 8.5), but all allude to a central premise of this work – that later-stage design is fundamentally different to early-stage design in terms of designer behaviour, and so must be considered as a research subject in its own right.

Later-stage design can therefore be said to differ in terms of activity focus (Pahl and Beitz, 1984), constraint (McGinnis and Ullman, 1990, Howard et al., 2011), complexity (Eckert et al., 2012), and the actual appearance of designer behaviour. As a result there is necessity to consider it separately to early-stage design and the design process in general, comparing and contrasting between each.

11.4 Creative Behaviour and Creative Approach

The field of creativity research has been a source throughout this work for theoretical understanding and structure, upon which research has occurred. Through the strict focus of the field of creativity on results that are by some interpretation better than their peers, and on the process by which these better results come to be, this background provides direction on better forms of designer behaviour, leading to better results.

Part of the use of the field of creativity has been through the structure of the four pillars of creativity (Rhodes, 1961). The main purpose of this is to in essence de-couple the study of the creative product from that of the creative person and process, and to highlight the potential lack of dependence between. The creative person and certain elements of the creative process, such as solution strategy when pre-decided, form an input to the design process, while the product forms an output. Depending on the type of transformation that occurs, the product may equally be of a creative or non-creative form; the presence of initial conditions for a creative result need not be assumed to guarantee their appearance as a result.

Creative behaviour in this work is interpreted through expansion within the designer's process (see Section 6.4); the active process of diverging or converging through exploration. In this way it is purely the actions of the designer that determine interpretation as creative or non-creative, there is no requirement for specificity of its study within context of particular processes, activities, or design stages. The context-free analysis framework and coding scheme then allow broad applicability of research and comparability of results.

11.4.1 The Appearance of Creative Behaviour

The first subject to consider in relation to creative behaviour within later-stage design is simply its appearance, specifically in context and comparison to early. Table 93 lists findings relating to the appearance of creative behaviour in the design process.

Table 93: Findings relating to the appearance of creative behaviour

Number	Section	Finding
1	Chap 7	Within the design process as a whole, creative behaviour is in a minority to non-creative behaviour.
2	Chap 7	Different designers will display varying quantities and forms of creative behaviour, whether completing different projects (as in study one) or the same (as in study two).
5	Chap 7	Later-stage design typically contains less creative behaviour than early-stage design.
12	Chap 8	Within later-stages, designers concentrate on non-creative methods of behaviour and structure development of the design.
15	Chap 8	During later-stage design, typical creative behaviour primarily concerns the determination of system behaviour and preliminary structure.
16	Chap 8	A high proportion of creative behaviour occurs in application-type tasks through both concept and embodiment design.
21	Chap 9	Experts demonstrate creative behaviour in their tasks, with suggestion of a higher proportion.

The appearance of expert creative behaviour

Across designers and projects, design situations and contexts, there is a variation in the proportion of creative behaviour that occurs in each designer's process. As would be suggested by the study of creative level (see Torrance, 2008), this would suggest that there is some form of pre-disposition between designers to display creative behaviour, be it due to a learned skill or an innate ability. As presented in Section 2.3, there are several personality-based reasons for this pattern, although these have not formed the primary focus of research within this thesis. Instead, this work considers the role of designer behaviour, and patterns of creative behaviour that appear within.

Some clarification can be placed on this when looking directly at the processes of experts, who also demonstrate creative behaviour within their tasks, but to a higher proportion (even when the design situation is identical). There is therefore also an implied suggestion that the acquisition of expertise brings with it an ability or tendency to complete creative behaviour. In this case creative behaviour can be considered either a learned trait, in that experts actively or passively employ it throughout their process as part of their more effective solution strategies; or creative behaviour can be considered an action that requires some level of expertise to employ in higher proportions.

In either case, should creative behaviour be the goal, there is some basis in literature for how it may be encouraged. For example, through such cases as creative problem framing (Schon, 1983), actively forming problems as ill-structured (Candy and Edmonds, 1997, Cross, 2004a), and always working on a first-principle basis (Cross, 2004a) (see Chapter 4). Taking the assumption that expert behaviour is an example of better practice than novice, as supported by results in this thesis (see Section 10.2), there is strong interest in any learnings that can be taken from the study of creative expert behaviour, a goal supported by the framework and coding scheme used within this thesis.

General creative behaviour

Looking purely at the appearance of creative behaviour, and not at the type of creative behaviour, there are some basic patterns of interest of relevance to the thesis aims. Although its appearance varies between designers, creative behaviour is consistently in a minority. This is particularly true in later-stages of design, in which the proportion of creative behaviour drops when compared to early-stage design.

There are a number of potential reasons for this, all of which form interesting directions for further research. The first concerns the necessity of creative behaviour, particularly in later stage design. Exploration by its nature involves the research and production of options and opportunities, whether or not they are followed. Given the highly constrained nature of later-stage design (McGinnis and Ullman, 1990), often focused more towards variant design processes (Howard et al., 2008a), there is perhaps simply lower necessity for creative behaviour in later-stage design. The designer is more likely to be able to see a path to solution, and therefore able to follow the easier solution (see Ward, 1994); a well-defined and non-creative schema (Dym, 1994, Gero, 1996, Brown, 1996). Relating back to expert processes, this lack of necessity may be countered by the techniques that they employ, in which they frame the problem in a manner that does not have an associated well-defined schema and hence requires creative behaviour (see Cross, 2004a). These findings therefore suggest that creative behaviour may not be necessary to the same extent within later-stage design as compared to early-stage, but that experts form their process in such a way to encourage it anyway.

A second reason for the lower appearance of creative behaviour in later-stage design is in suitability to the specific design situation. Given the specific conditions, the process of exploration may prove undesirable when compared to following a well-defined process; for example, when under strict time restrictions. As has been proposed by other researchers, the different requirements and design situation of complex design situations may require creativity of a different form (Eckert et al., 2012). This is a matter of context of design, and is further discussed in Section 11.5.

Such rationale in general forms a subject for further work. This thesis has demonstrated a lower proportion of creative behaviour than non-creative, and that the occurrence of creative behaviour decreases as the design process continues. Given that experts demonstrate a higher proportion of creative behaviour, and taking the assumption that this represents an example of better practice, there is some evidence that the occurrence of creative behaviour in later-stage design should be increased. The goal of further work would then be to explore this connection; through forcing creative exploration in later-stage design, output quality could potentially be increased. Similarly, it could be through the alternative methods of passing through a design process, which inherently stimulate creative behaviour, that experts produce higher quality output. In this case, it would be through the mimicry of experts that non-experts could improve their output. Such questions provide avenue for further work.

Later-stage design creative behaviour

As stated within Section 3.3, the later-stages of the engineering design process are concerned primarily with the development of system behaviour and system structure. As shown by findings fifteen and sixteen, this pattern continues into the occurrence of creative behaviour in that it is also primarily concerned with the development of system behaviour and system structure.

This is not a surprising finding given the nature of later-stage design as application-type task focused. Particularly for expert designers, the knowledge that they hold allows them to reduce the necessity of information-type tasks. This same ability would also lower the requirement to perform creative behaviour in information-type tasks; their focus can lie near-entirely on application in order to produce a solution.

In cases of non-expertise, however, the situation may differ. When the designer does not hold expertise and the pre-requisite information to produce a solution is not present, a creative approach to gathering such information may be more beneficial. This finding therefore mirrors that already stated; through improvement of information-type tasks, the behaviour of non-experts may be encouraged to produce better results.

11.4.2 Patterns in Creative Behaviour

Many of the findings presented in Chapters Eight and Nine demonstrate not only creative behaviour, but certain patterns in creative behaviour that exist throughout the later-stage design process. It is these patterns that form a useful and interesting subject in the research, as they provide a deeper understanding of the form of creative behaviour and how it may be encouraged to occur. Table 94 lists findings relating to patterns in creative behaviour.

Table 94: Findings relating to patterns in creative behaviour

No.	Section	Finding
3	Chap 7	Different designers will display different creative approaches within later stages of the design process, even when completing identical projects.
4	Chap 7	Creative behaviour within later design stages correlates significantly with creative style.
6	Chap 7	Designers more frequently display more creative behaviour when completing cross-entity tasks.
13	Chap 8	Cross-entity tasks are consistently creative throughout the entirety of the design process; in a minority during early-stage design, and a majority during later-stage design, when compared to within-entity type tasks.
14	Chap 8	More creative designers will follow an effectuating approach during later-stage design processes.
17	Chap 8	Despite preference for one over the other, a designer’s creative approach can vary through the design process. Some designers remain astute in later-stage design, while others become effectuating.
23	Chap 9	Experts consistently follow an effectuating approach in later-stage design, suggesting superiority or higher approach suitability.
24	Chap 9	Experts are more often creative in cross-entity type tasks, to a higher proportion than non-experts.
25	Chap 9	Better design behaviour can be characterised by a majority proportion of creative cross-entity tasks.

Approaches by output type

One of the main assertions of the framework and coding scheme used within this work is in the different forms of creative behaviour that a designer can utilise throughout their design process, determined through the output of each. These creative approaches bear close resemblance the types of creative behaviour proposed within literature (Gero, 1996, Dym, 1994). Several of the findings presented in this work confirm this assertion, in that designers were observed as completing creative behaviour in different types of task, following certain patterns.

The foremost of these patterns is simply in the appearance of differing majorities of creative behaviours as displayed by different designers, even when the design situation in which they are working is identical. Within each stage of design, there are multiple pathways to creativity. The *astute* approach primarily involves the exploration of the design space through the knowledge and variables available at the outset of the design process, or that can be used in the design process. In this way, a typical result of a creative act would be distinguished through an introduction of something new into the design – for example the use of a new technology, a fundamental change in solution principle, or alteration in manufacturing method. The *effectuating* approach primarily involves the exploration of the design space through how current existing and known knowledge and variables can be used in the design itself. A creative act would then be seen through a change in the manner of application of a design, such as through part count reduction, optimisation of performance or layout, or refinement for manufacture.

That these differing approaches exist in an identical design situation is particularly important, especially when considering only those designers that also held similar experience. This suggests that the use of differing design approaches should be considered with a certain level of context-independence; the designers will not default to a certain approach based on the conditions of the design situation. The appearance of a design approach is therefore to some extent a result of individual difference (such as through personality or motivation). Patterns of behaviour based on personality and individual difference are recognised in literature, such as differences between scientific and artistic creativity (Feist, 1999), working behaviour based on problem-solving style (Eisentraut, 1997), and the creative style test itself (Kirton, 1976).

Finding seventeen states that, in addition to the fundamental appearance of a creative approach, the approach of a designer can change as the design process continues; generally from primarily astute to primarily effectuating. Given the structure of the design process as a switch from information-type tasks to application-type tasks a switch of this form is not a surprising discovery. It is useful however to be aware that the behaviour of designers, including the creative behaviour of designers, can alter as the design process continues. As a result, dependent on the suitability of differing approaches at differing design stages, there is scope to streamline and enhance the process that designers follow by altering their approach.

Given then that designers can employ differing creative approaches in design, and that their approach can vary through the process, a question arises of the approach that is more suitable to later-stage design. Both findings fourteen and twenty-three support the proposal that despite potential individual difference, an *effectuating* approach is the more effective, both in terms of producing a result that is judged as creative, and in terms of producing a result that is of higher quality.

To some extent, this is an expected finding; a reasonable body of evidence has been presented so far stating that application-type tasks (which are effectuating when completed creatively) are more common in later-stage design, and that this is a positive characteristic. Creative behaviour in application-type tasks would therefore signify the attempt to improve results from the task-type that dominates the design stage. Furthermore, the lack of information-type tasks performed by experts within later-stage design would suggest that, as no information-type tasks are needed, there also need not be creative information-type tasks.

Conversely, however, given that non-experts do not hold sufficient expertise to progress without explicit information gathering (see Section 4.2), it is a necessity that they do perform information-type tasks, and so, as these tasks form the basis on which the design is produced, it would be beneficial for these tasks to be completed in an expansive manner. The effectuating majority demonstrated by experts can in this case be considered a learned trait based on their own experience, in which the *need* for an astute approach diminishes, but does not demonstrate that an astute approach would be inherently *non-beneficial*.

Creative behaviour in later-stage design therefore presents a reasonably complex picture. Particularly when studying non-experts, multiple approaches exist. These approaches are to some extent dependent on the personal approach of the designer. However, there is also a strong influence based on suitability and necessity within the design process stage. As later-stage design does not require a significant occurrence of information-type tasks when sufficient information is present (in the case of the expert designer), there is a corresponding drop in occurrence of an astute approach at these stages. Although also a result of individual experience within the designer, such a drop indicates that the appearance of a creative approach is not innate and unchanging, and hence not purely the result of personality differences as exist when comparing between different fields (see Feist, 1999).

Creative approaches therefore become a medium through which the design process can be influenced for the purpose of improvement. Particularly in the case of non-experts, following an astute approach to ensure optimal information and knowledge resource should provide the basis to produce a strong design, following which an effectuating approach will ensure the result of design is also of quality. For an expert, although it may not be necessary to complete any astute tasks, stimulating their occurrence will encourage the designer to re-evaluate their personal experience and how it is used, potentially with the benefit of uncovering new opportunities. Their typical effectuating approach would then prove a valuable method of turning these new opportunities into useful solutions.

There is significant scope beyond the findings relating to creative approach for further work. Discussion of suitability and necessity of approaches as presented here suggests scope for improving the output of the design process, but these suggestions need to be explored and validated. In reality, the processes by which the approach of a designer can be altered are not known; nor are the actual results of such an alteration. With the identification of approach and patterns that exist, however, this thesis provides the basis on which further work can be completed.

Approaches by transformation type

Considering creative approach through transformation type presents a far less complex picture. This category concerns the distinction between tasks that have an input and output of the same type, and an input and output of different types. The former would then typically be represented by such tasks as clarification of information or gathering of further detail on a subject; or of refinement of dimensions and configuration design. The latter would typically be represented by the implementation of a function into a system, or the evaluation of a part against its specification.

Almost without exception, designers were more often creative when completing cross-entity type tasks than within-entity type. This is a significant finding about the nature of creative behaviour in later-stage design. Furthermore, as stated by findings twenty-four and twenty-five, there is a level of better practice also to be associated with the completion of creative cross-entity tasks.

There seems, therefore, to be some fundamental link between the transformation from an entity of one type to another and the requirement for exploration. Relating to the types of creative and non-creative behaviour of Dym (1994), this relationship can be clarified. When developing an entity into a more developed form of itself there is a clear conceptual link, in that the subject and form of the output can often be described in its relation to the input. For example, when completing dimensioning tasks, the designer is taking a developed form, and finalising the sizes of each aspect – they take a geometrical input and develop it to a more detailed form of itself. In these cases, there is a well-defined schema available to the designer; they know their inputs, they know a sufficient amount about the form their output will take, and they know what must be done to transform one into the other.

Due to the transfer between entity types within cross-entity type tasks, there is potentially less indication of path to output or the result that the output will take. The disjunction between individual variables and pieces of information and the way in which they manifest within a design creates a lack of clarity to solution; each such transformation can be completed in a number of different ways and, particularly when the designer is of lower experience, they will have less idea of how the transformation may occur. As a result, there is wide potential for unprompted exploration in cross-entity tasks.

The stimulation of cross-entity tasks then serves as a potential method for the support and enhancement of designer process. Should a creative process and creative result be desired, stimulating the designer to complete a higher proportion of cross-entity tasks could be the initiator. Similarly, should a creative process not be desired, stimulating a higher proportion of within-entity tasks could have the appropriate effect.

11.4.3 Correlation with External Measures

Within Chapters Eight and Nine some correlation with external measures was found. Of these correlations, Finding Four suggests some relationship between creative approach as identified within this work and the individual creative styles of the designers as determined by a creative style test.

This relationship is however not entirely clear, and deserves some further attention. Findings of correlation against external measures are listed in Table 95.

Table 95: Findings relating to correlation

Number	Section	Finding
4	Chap 7	Creative behaviour within later design stages correlates significantly with creative style.
8	Chap 7	Creative level is related to the proportion of tasks completed in an astute manner.

Consideration of the creative style test

The creative style test was initially proposed as a method of identifying different styles of creative behaviour. However, as demonstrated within the literature, in practice it also correlates with creative level (Isaksen and Puccio, 1988). This dual purpose is a result of a lack of clarity and independence between creative style and creative level in the creative style test. To understand the reasons for correlation between the creative style test then, and the reason for its increasing of validity of the framework and coding scheme, more detailed analysis is needed of what exactly the test measures.

As stated by Kirton (1978), the KAI scale measures style of creativity, and not level. However, the distinction in what Kirton describes as a style is less clear. By his interpretation, an *adaptive* creative style is one in which the designer works in detail within existing paradigms to adapt their situation to a solution. The *innovator* is one who will follow a different approach, and is willing to explore how their design can be adapted to solve problems or develop the solution with no regard to remaining within known paradigms.

Creative behaviour as defined in this work is through the act of expansion in a process; the active attempt to explore the design space and produce alternatives, or to produce alternatives through evaluation and combination. Comparing this to the styles of Kirton, the *innovator* matches closely. In order to identify different solution paradigms and adapt their design situation to solve problems, they must explore. Logically, then, there should be correlation between the quantity of creative behaviour identified through the framework and coding scheme, and the strength of *innovator* style of the KAI scale. This relationship exists in all studies with sufficient participants to measure significance, and is formalised in finding four.

The *adaptive* style of Kirton, however, is not creative through exploration to the same extent as the *innovator*. By his description, they are not creative through exploration around solution principles, concepts and paradigms, but rather in their use of existing paradigms for their design situation. This then refers not to exploration throughout their process, but rather exploration in the initial paradigms to use. Once the *adaptive* designer has identified viable paradigms, they need not then proceed in an explorative manner. By this method, the designer is not necessarily creative in their design behaviour, but rather in their method of identification of solution strategy. Because of their *adaptive* strengths, they do not need to explore, and thus potentially make the path to solution clearer and simpler.

However, this *adaptive* form of creativity is different in principle to that studied within this work. The creative behaviour of the designer does not relate to their design behaviour in development of a product so much as it relates to their identification of solution strategy. For example, their creative act could be through the selection of a solution principle of working from first principle (a trait of expert design, see Cross (2004a)) rather than through exploration in their design behaviour. As such, the *adaptive* design should not be expected to correlate with creative behaviour as identified within this work. This thinking of an *adaptive* creative style as fundamentally different from typical creative behaviour is also reflected in literature, both by those who recognise *innovative* design as the more creative (Isaksen and Puccio, 1988), and by Kirton in his initial proposal of creative styles (Kirton, 1976).

That correlation exists between creative behaviour as defined within this work and the score on the creative style test then provides validity to the results of the framework and coding scheme. The stronger a designer's classification as an *innovator*, the more often they will be identified as completing creative behaviour.

Creative level and creative approach

The Torrance Tests of Creative Thinking (TTCT) (Torrance, 2008) were used in study two to determine the creative level of each of the non-expert participants. These tests determine the creative level of a designer based on the output of their working within specifically designed tasks, which imply particular personal traits and characteristics.

There is then some difference in assessment of creative level by the TTCT and of creative behaviour as measured by expansion in tasks. For a designer's output to be judged as creative by the TTCT, they need not complete a significant proportion of their process in a creative manner – they need only to produce an output with particular characteristics. While some creative behaviour must occur for a creative result to be produced, the TTCT makes no assumption of the frequency of occurrence outside of a single creative episode, only that the creative behaviour produced a result of sufficient appropriateness or novelty to be interpreted as creative. Relating to the results of the framework and coding scheme, this suggests that frequency of occurrence of creative behaviour in multiple episodes need not correlate with creative level. The completion of creative behaviour does not imply that the results will be creative, only that the designer then has higher potential of producing results that are creative. The closest argument that could be made between the two measurements is perhaps that a higher TTCT score would imply higher "quality" creative behaviour, in that a lower frequency of occurrence could still lead to a highly creative result. Such a classification has not been the focus of work within this thesis – the appearance of creative behaviour is taken as-is, without judgement of its "quality". There is therefore no expectation for correlation between creative level and the fundamental appearance of creative behaviour.

One correlation was found, however, between creative level and creative approach; that of a significant relationship between strength of an *astute* approach within later-stage design and creative level as measured by the TTCT (finding eight). This correlation shows some similarity to discussion of the necessity for information-type tasks within later-stage design. As evidenced by the experts, within later-stage design these is less need to complete information output tasks, instead focusing on producing the actual design. That those who are more astute in later-stage design (an approach that may not be needed according to other findings) are also of higher creative level, then suggests that the following of application-type tasks in later-stage design is more equivalent to the following of a well-defined, non-creative schema. It is not necessary to complete creative information-type tasks, but those designers that by creative level produce results that are more original will complete them anyway. This shows further individual difference in creative approach, those of higher creative level are more likely to complete later-stage design in a different manner than is necessary, at the potential benefit of producing an original result.

Considering that the TTCT test does not imply quality in output, only other characteristics based on personal traits, it is interesting to consider that a higher creative level and accompanying higher proportion of astute type tasks will not necessarily lead to better results, only to results that are original. It is therefore not necessarily wise to recommend an astute later-stage approach to increase output quality, only to increase output originality.

11.4.4 Design Behaviour and Quality

Through the quality analysis completed upon the output of study two, some understanding of the occurrence of better results can be gained, and the potential behavioural conditions that led to them. Table 96 lists findings relating to quality or some form of superiority in designs.

Table 96: Findings relating to design behaviour and output quality

Number	Section	Finding
10	Chap 7	Design quality, as judged by experts, is related to a focus on application type tasks, and a higher frequency of occurrence of creative behaviour.
18	Chap 8	By expert judgement, high quality is more dependent on later-stage creative behaviour, a late-stage focus on application-type tasks, and an early-stage focus on creative information-type tasks.
19	Chap 9	In the same design situation, the design solutions of experts are often better than non-experts, both according to metric-based assessment and expert judgement.
20	Chap 9	By the assessment of an experienced human observer, when based against the definition of creative products, expert designers will produce a more creative solution than non-experts in an identical design situation.

Correlates of quality

First, some comment must be made of the validity of the quality and creativity assessment made within this work. Following the judge-based assessment method (see Amabile, 1996), both quality and creativity are interpretations based on the expertise and opinion of people with experience within the field. There is therefore an assumption that their opinions are valid (Potter and Levine Donnerstein, 1999) and representative of, in this case, higher quality and creativity.

As this method relies on judgement of experts, which is by its nature field-specific, the metric-based assessment method was also employed. This gives a non-biased assessment based off of the specification. That significant correlation between quality as judged by each of these methods exists provides confidence that both are valid.

Looking first at findings ten and eighteen, some understanding of the implications of behaviour types in design can be gained. In both cases, better quality in result is interpreted as coming from specific types of behaviour. In finding ten, as in the processes of experts as discussed, a focus on application type tasks is found to lead to a higher quality result. Particularly in later-stage design, and by the other findings within this thesis, this acts as confirmation of results that have already been stated. All designers focus on application-type tasks in later-stages (experts to a higher extent than non-experts) due to a lower necessity for information-type tasks. Assuming that the process of experts represents better practice in design, a higher quality result from a higher focus on application-type tasks is to be expected.

There may, however, be some discrepancy in this result based on design situation. In study two, from which quality assessment occurred, the designers were under significant time pressure. As a result, each final solution was at a similar but non-identical level of completion dependent on the working speed of the designer. As the higher quality results were a correlate of the expert-judged method (which is subject to interpretation) and not to the metric-judged method (which is not), it is possible that higher quality is an interpretation of level of completion. When it is clear that a design is well-progressed and near complete, there may be some tendency for it to be judged as better than a design of lower completion. In such an example, a focus on application-type tasks could be said to be representative of designers working efficiently and reaching a high level of completion in a shorter period of time, rather than of actual quality of output.

An addition to this thinking is that higher quality showed relationship to the occurrence of later-stage creative behaviour (Finding Eighteen). Given that a creative result is considered to be one that is of more appropriate quality to the design situation, there is in this finding an element of creative behaviour linking to creative result. Particularly in later-stage design, there is an argument to be made regarding the act of creative behaviour and its purpose. As opposed to an early-stage design focus on concept design and system function, later-stage design focuses on the behaviour and structure of a system. Creative behaviour within later-stage design will therefore also demonstrate this focus; as such it will not be concerned with the identification of system functions, and rather will explore different options of generating desired behaviour from structure. Creative behaviour then focuses on better ways of generating behaviour and forming structure, acts that imply the production of better system performance and organisation. Should this be the case, creative behaviour in later-stage design can be considered the process by which higher quality in solution is ensured.

Expert behaviour and quality

Both findings nineteen and twenty relate to the relationship between the results of expert working and non-expert working. One assumption taken within study three, and the thesis in general, has been that expert designers produce better work than non-experts, and so that their process represents an example of better practice. It is based on this assumption that much work on the processes of experts has occurred (see Ericsson and Lehmann, 1996, Cross, 2004a, Cross, 2004b).

As evidence to this assumption, this work compared the output of an identical design situation as completed by both experts and non-experts, assessing each both according to expert opinion and according to the brief specification. In each case, the experts were found to produce higher quality results than the non-experts, supporting the proposition of their working practice producing better results. The working practice of experts can therefore be taken as a source for study, as has been performed throughout this thesis.

Additionally, expert designers were found to produce a more creative design solution than non-experts, as interpreted by an expert judge. This therefore suggests two points. First that the behaviour of experts is a potential source of understanding for the identification of creative behaviour; and second that there is some relationship between creative behaviour and output quality. This second point is also supported by finding eighteen. The implication of these points is in further confirmation, a link between creative behaviour and quality gives confidence in the study of creativity as a method to improve working practice, and in turn improve design quality.

11.5 The Role of the Industry Context

Within Chapter 10, the important subject of wider project context was explored through study three. Although fewer formal findings were given on this subject, it remains important to discuss.

In essence, study three formed an analysis of the effect of the context in which each study occurred, and the potential resulting influence on the behaviour of the designers. While the results of both studies one and two can be described as valid in themselves, some further analysis of the results in a realistic setting is required. It was to this end that the observational aspects of study three were completed, providing additional information on the behaviour of designers within a more realistic design situation.

11.5.1 Project Context

As listed in Table 97, the individual brief of the designers within study three was found to have a likely impact on the behaviour that they demonstrated.

Table 97: Finding relating to project context and designer behaviour

Number	Section	Finding
26	Chap 9	The expectation within a project will alter the appearance of creative behaviour of a designer in industry.

This finding was not present in either study one or two due to the similarity in their briefs. Within study two, the design situation was identical – all difference in the behaviour of designers was a result of their own process. In study one the briefs were all different but very similar in expectation of working – the designers were to produce a working proof-of-principle prototype. These were all products for the open market of some form, and required the designer to progress through a significant section of a largely typical design process.

Study four, on the other hand, focused on the highly specific projects upon which each participant was working at the time of recording – no pre-selection occurred. As a result, the projects could have any desired output within the scope of the designer's usual work, and encompassed much smaller proportions of the design process. The scope of the study therefore allowed the influence of the individual project on designer behaviour to be seen.

This point also demonstrates the place of Finding twenty-six in contrast to Finding two, which states that designers will demonstrate varying creative approaches regardless of whether their projects are identical or different. Again, within study one and two the expectation and situation of design were similar and comparable, and the designers were under little expectation apart from the need for progression. In study three, the expectation strayed from this case, with designer 4A, for example, working on a brief that was severely limited in potential for exploration; and designer 4B working on a project that required extensive exploration for any progress (see Section 10.4). The culmination of these two findings then states that the project may have conditions that encourage or restrict creative behaviour, but when the scope for creative behaviour and expectation within the industrial context is identical, designers' approaches will vary independent of the actual output that the brief demands.

It is also to be noted at this point that these results demonstrate that the project will influence the behaviour of the designer. This is not in conflict with finding three which states that different designers will demonstrate different approaches in the same design situation. In any of the projects of study three, a different designer to the one studied may have been influenced in an identical or different manner, and may have displayed an identical or differing approach. What finding twenty-six does tell us is that some influence from the project can occur.

By way of reminder, in project 7 of study three, the designer was required to complete explorative behaviour in order to reach their project goal – the production of a variety of concept variants for simulation. Accordingly, the coding scheme identified a higher proportion of creative behaviour than the same participant had displayed in study two. In contrast, project 4 required the participant to review form and finalise dimensions for a design to be sent for prototyping, along with the addition of some smaller design features. Their project goal in this case was expected to be a single model, formed from a highly developed, pre-existing version. In this case, they were not expected to complete any creative design, rather to quickly review and continue. Accordingly, the coding scheme identified a smaller proportion of creative behaviour than the same participant displayed in study two. The impact of these findings is in validity of results in an industrial setting, and scope for the support and enhancement of the design process.

Both studies one and two are valid in and of themselves, and can be contrasted against one another. They found similar behavioural patterns across the two design situations, with understandable justification for differences. Study four extends the understanding of the role of designer behaviour to also be reliant on the expected output of the design brief, but again in an understandable manner. In cases in which creative behaviour is not to be expected, the designer will demonstrate lower quantities of creative behaviour. In cases in which it is to be expected, the designer will demonstrate higher quantities of creative behaviour. These comments strongly echo thoughts on the definition of routine design (Brown, 1996). There are cases in design where a creative approach is the expected and usual method taken; therefore forming the "routine", or typical, solution strategy. As argued by Brown (1996) then, creative behaviour and routine behaviour should be considered as separate phenomena – dependent on what could be termed the norm in each designer situation, different types of behaviour can be expected to occur. These thoughts are similar to others within literature, which describe the project scope as an influencer on solution strategy (Clark, 1989, Ichniowski et al., 1996), and the performance of individuals as dependent on several aspects of design situation (Waldman, 1994).

For the results in this thesis then, this thinking serves as an extension into further work. All results presented within Chapters Eight and Nine are valid in typical design situations as seen in many design process models (see Hales, 1986, Pahl and Beitz, 1984, Pugh, 1990, Cross, 2000), including in typically defined later-stage design. When considering quite specific design situations in industry however, some variation can be expected to occur. While the work within this thesis has presented a detailed characterisation of later-stage design behaviour, it has also uncovered a further research question, broad in nature, which can be applied to the study of industry: *In what way does the expectation of output within industry influence individual designer behaviour?* Such questions are considered too significant in scale to lie within the primary research scope of this thesis, but do have greater implications in industry – before the findings and discussion of this study can be applied in broader context, it is necessary to understand all of the varying influences to which industry designers are subject, and the specific ways that those influences will alter their behaviour.

As will be discussed, once expectations of behaviour are known, the findings within this study can be used to support and enhance the design process.

11.5.2 Specific Influences on Designer Behaviour

While broader study of this subject is needed, some influencers of design behaviour have been identified within this work. Table 98 lists findings relating to the specific influence of the design situation on the designers.

Table 98: Findings relating to time restrictions

Number	Section	Finding
7	Chap 7	The proportion of within-entity tasks to cross-entity tasks is in part indicative of the design situation and process streamlining.
9	Chap 7	In a time dependent situation, design quality is related to the number of discrete tasks completed by a designer.

Within literature, there are some examples of study of the influence of the specific design situation on the individual performance of designers. For example, discussion of the importance of maintaining "place", in which the designers are comfortable in their working environment (Harrison and Dourish, 1996), the effect of the environment on creativity (Amabile et al., 1996, Csikszentmihalyi, 1999), and the effect of individuals on team performance (Barrick et al., 1998, Thamhain and Wilemon, 1987). These factors were mitigated against in the study procedures, by ensuring that the designers were working in a realistic and familiar environment in each study, and by the exclusive study of individuals within design.

A further influencer within the literature is the effect of time and pressure on designer performance (see Kelly and McGrath, 1985, Andrews and Farris, 1972). Unlike these examples in literature however, which have studied the effect of time and pressure on process output, this thesis is able to suggest some relationship between the effect of time and pressure on actual designer behaviour.

Within both studies one and four designers completed a smaller proportion of within-entity type tasks; while in study two within-entity type tasks were in a clear majority)(Finding Seven). Between studies one and two the primary difference was the design situation in which each designer was working, with study two involving significant time restrictions. Between studies two and four there was also a major difference in design situation due to time, although these studies also differed in terms of design task. It is then perhaps telling that both studies one and four, in which time was not a major concern, demonstrated a lower proportion of within-entity type tasks when compared to cross-entity type tasks, and that this pattern is reversed when the designers are under pressure.

As cross-entity tasks inherently involve more complex transformation than within-entity (Section 11.4.2), and are more often performed in a creative manner, it is possible that their minimisation in the time-restricted situation is reflective of the designers making an effort to increase the rate of their progression. Should they not need to explore or perform transformations from one entity type to another, they may be able to streamline their design process. There is evidence within literature for this proposal, in that designers will commonly choose the easier solution strategy when designing (Ward, 1994, Moreau and Dahl, 2005); perhaps the reduction of cross-entity tasks removes the need to explore, consequently making a path to solution clearer, and increasing rate of progression through the design process. The trait of expert designers to structure their problems as ill-defined (Cross, 2004a, Candy and Edmonds, 1997) could then be reflective of a desire to stimulate creative behaviour through cross-entity tasks.

A similar finding was also found in study three, in that designers completed a higher proportion of information-type tasks in later-stage design than in study two. In this case the proportions were not as high as in study one, but still demonstrated a potential implication of a restricted time situation. In order to increase their rate of progress in study two, the designers focused on the actual design and its production, ignoring potential information tasks (hence cross-entity tasks in many cases) in order to streamline their design process.

This is further supported by finding nine, which found higher quality as a result of a higher rate of working. This demonstrates the benefit of a higher work rate; when unable to refine and optimise the design due to a lack of time, it is of benefit for the designer to streamline their process to reach as high a level of completion as possible.

This claim is perhaps strong based on the evidence within the studies, but does suggest a strong direction for further research. It is logical that a designer's process would alter when time is a major factor, in order to ensure a solution is reached within the time period. This behavioural change would manifest in the types of task that the designers completed and their creative qualities. Through study of the effect of time on actual designer behaviour then, it may prove possible to stimulate designers towards behaviour that greatly increases their rate of working, increases the quality of their output, or increases output creativity.

11.5.3 The Necessity of Creative Behaviour

One subject that has not been addressed within this thesis is the appropriateness of creative behaviour at all within the later-stage design process, or indeed its applicability and usefulness across design situations.

Due to the definition of a creative product as by some manner better than a non-creative product (Chapter 2), and the requirement for creative behaviour to occur for a creative product to be developed, it follows that creative behaviour should be a positive occurrence.

When considering project context, however, examples can be found in which creative behaviour is not a desirable part of the design process. Within this thesis, project 4 within study three presented a case in which the designer was not expected to explore by any method, and instead reviewed a design, quickly added small details, and sent the design for prototyping. In other cases where constraint is particularly high or the risk of change propagation is high, it may also be undesirable to explore or attempt to produce a creative result – although the output would prove better than the initial version of the design, the process to reach the better output may be too time consuming or too expensive to be feasible.

These thoughts form another area for further work and consideration when attempting to match behaviour to a design situation, but also show the potential benefits of such knowledge. As has been found within this work, if the designer requires a non-creative approach and a non-creative output, they are better to focus on within-entity type tasks, and make a smooth transition from a high majority of information-type tasks in early-stage design to application-type tasks in later-stage design. Should the designer require creative behaviour for their process, or desire a better solution than would be found through non-creative means, they should stimulate a high proportion of cross-entity type tasks, and consistently employ information-type tasks well into later-stage design to ensure their knowledge and resources present good opportunities.

In reality, the exact requirements and influences of any design situation are likely to be highly context-dependent, varying based on individual project requirements, company, designer, and design team. Regardless of such influences and requirements, however, should the designer know what they desire in terms of creativity within process and output, the findings of this thesis are able to provide recommendations for the types of task they should complete, and the approach that they should follow.

11.6 Study Findings and Existing Research

Much of the literature presented within this thesis, particularly that within Chapter 4, is highly relevant to or studied within the body of research dedicated to designer thinking. Rather than focus on the prescriptive models of design (see Pahl and Beitz, 1984, Pugh, 1990), this work appreciates the flexible nature of the individuals design process, in which methods are applied as needed and at the preference of the designer (Stempfle and Badke-Schaub, 2002).

It is interesting to consider the findings within this thesis from the perspective of the body of work on design thinking. While the coding scheme operates on a different level of abstraction to that of the mental processes of designers, and as such the relationship between its results and literature on design thinking requires further investigation and study, there is sufficient detail and overlap to evidence common themes within design thinking in the scheme findings.

There is potential for cross-entity tasks to be representative of the co-evolutionary design process as studied by Dorst and Cross (2001) and Maher and Poon (1995). Co-evolution proposes design as a series of iterative transformations between a problem state and a solution state. In practice, this problem state represents all that is known about the design including the requirements, solution alternatives, and their evaluation, while the solution state contains conjectures for designs that will meet the brief in an appropriate manner. Design itself is then considered to be iteration between these two states, in which the designer forms a solution conjecture, assesses it against their requirements and uses it to re-define the problem state (clarifying requirements or informing of viability of different solutions, for example). This re-defined problem state is then used as a basis to suggest a new solution state, and so on. As such, co-evolution describes both the method by which designers clarify their problem, thereby part of their method of seeking information and clarifying their task, and the way in which they use that information and clarified task to form a discrete output.

Interest comes from the comparison of problem and solution states to information-type and application-type tasks. An information-type task is one that focuses on the resources and requirements of design, therefore containing the information that describes the problem. In addition, when analysis or evaluation of a design yields results, it informs and re-defines the information that is present for design. As such, despite not being synonymous, there is a commonality between information-type tasks and developing and redefining the problem state of a design. An application-type task bears to the formation of solution-conjecture, therefore describing the solution-state of a design. Through the exploration of solution conjectures and development of configurations and parts, a designer is forming a series of possibilities that describe the form that a solution may take. Information-type tasks could then be seen as part of behaviour that develops information and clarifies the task, while application-type tasks could be seen as part of behaviour that produces both intermediate and the final solution conjecture.

This potential iteration is evidenced throughout the findings of the studies within this thesis. The high proportion of information-type tasks in early design stages (those that are for the purpose of task analysis and conceptual design; finding eleven) could be representative of information seeking behaviour and task clarification through the development of information at stages when lower information is present. Within embodiment and detail design, there is a high proportion of both information-type and application-type tasks, perhaps indicating the formation of solution conjectures and subsequent redefinition of the problem space in the process of developing a final output. Through more detailed study, a clearer relationship between the theory of co-evolution and capabilities of the coding scheme may be formed, through which the co-evolutionary design process, and hence the specific and detailed individual process of design, may be understood.

A particularly interesting potential relationship exists when looking at task transformation type, specifically that cross-entity type tasks could then be considered reflective of the transfer between problem-state and solution-state as performed by the designer. An [I → A] transformation is the process of forming a physical or virtual design based on the information present for development, including the problem description. The process of forming a solution conjecture within a solution state, based on a certain problem state therefore shows some similarity. An [A → I] transformation takes a certain design output and uses it to develop information present. One interpretation of this could then be the use of a certain solution conjecture as a basis from which to redefine the problem state, as occurs in co-evolutionary theory. While further work would be required to fully study the relationship between these task types and co-evolution, the similarity between types of task, the ability of the coding scheme to detect them, and the frequency of their detection throughout the results provides support both for co-evolution as a concept and for the scheme as valid.

This relationship is particularly interesting when considering that the transfer between problem-state and solution-state within co-evolution is thought to be a fundamental part of the creative process, in which both states are highly unstable until the point at which a "bridge" between them is formed, suddenly becoming the basis for a creative solution (Dorst and Cross, 2001, Cross, 1997). Within this work, cross-entity tasks were identified as more frequently occurring in a creative manner (findings six and thirteen), with creative tasks particularly common through concept and embodiment stages of design. Cross-entity tasks could then represent this unstable nature of the relationship between problem and solution states, in which the frequent iteration and redefinition of each through creative exploration is used as a basis on which to form a common ground for understanding, and the eventual path to a valid solution. Once the creative bridge has been formed through cross-entity tasks, there is less exploration required to reach a solution and so, as this work has evidenced, in detail stages the occurrence of creative behaviour decreases. This is particularly supported by the maintenance of a high proportion of both creative information-type and creative application-type tasks through concept and embodiment design stages, perhaps indicating a high proportion of co-evolution throughout each. Such thoughts require specific validation in further work, but do indicate a likely and significant relationship between the coding scheme and existing theory.

11.6.1 Findings and design behaviour research

One important and useful element of the framework and coding scheme is its content neutrality, in that it is able to study the behaviour of designers independent of the work that they are completing, and without the subject of their working affecting the coding in any way. This is important in order to maintain broad applicability of the scheme to a number of design situations, thereby allowing and learning from the comparison of differing design situations, different designers, and different levels of expertise. As a result, the analysis completed within this work does not study the content of the design process, only the individual abstracted tasks completed by the designers through their process.

This has an implication for the comparison of findings from the thesis directly with concepts within literature on designer behaviour within engineering design, as presented in Chapter 4. Concepts such as problem framing (Section 4.2.2), problem structuring (Section 4.2.3), and fixation in design (Section 4.2.4) all require knowledge of the subject of that which is being designed for their study. For example, to study reflective practice (Schon, 1983) it is necessary to study the concepts and perspectives used for design of the individual output, and to identify fixation (Jansson and Smith, 1991, Purcell and Gero, 1996) it is necessary to track the concepts produced through the process. It is not then within capability (nor the remit) of the coding scheme to directly analyse such subjects.

However, through elaboration and more detailed study of the raw data, such subjects could be informed. With knowledge and analysis of concepts through the design process, tied to the types of task completed by the designers throughout their process, there is potential to gain understanding of the behaviour of designers in each of these subjects. For example, by devising a method to classify and track reflection within design, application of the coding scheme could elucidate the behaviour and process by which reflection occurs, and the creative qualities that it displays.

I am content-neutral in the scheme, which is important to maintain focus on behaviour, and to be context neutral. Much of the study of design thinking requires non-neutrality in content.

11.6.2 The four pillars of creativity

In the initial stages of this thesis, the four pillars of creativity were presented as a basis on which the framework and coding scheme were developed and research completed (Section 2.1 and 2.6), and were summarised with Figure 45.

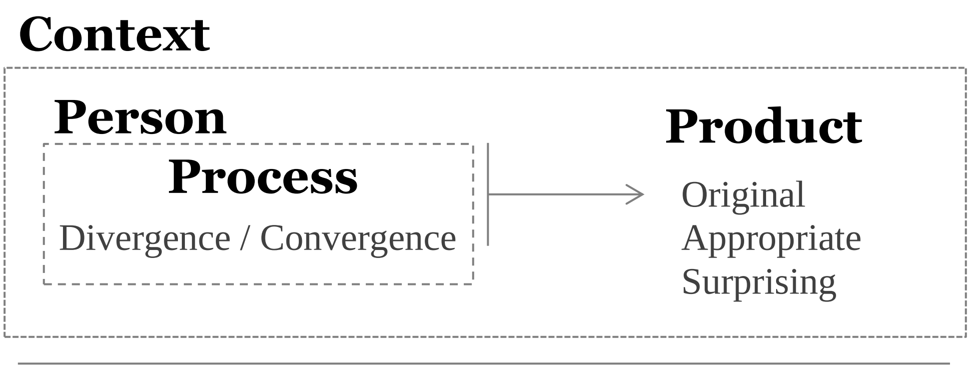


Figure 45: The four pillars of creativity as structure within this work

The purpose of this structuring was to allow deeper understanding of how creative behaviour may manifest throughout the design process and the product, how it may be interpreted, and how it may be influenced. This structure has been maintained throughout the work as a useful reference to the study as completed, allowing clearer understanding of the concept of creativity.

As highlighted by the four pillars, creativity does not manifest only in the product that is the output of design; its appearance is the result of a person and the process that they choose to follow, and the context in which they work. As this work has placed focus on the study of the behaviour of designers within later-stages of engineering design, it is the person, process, and context pillars that are considered of most interest; although it could be hoped that a more creative process leads to a higher likelihood of creative output, it was inappropriate to assume that this would be so. In reality, as evidenced by higher creativity in process of experts and higher creativity in output (findings twenty and twenty-one), this assumption could perhaps have some validity.

The structure of the remaining three pillars and literature as used within this thesis also implies some assumptions; namely that the process is individual to the designer, that there may be variance in the process in order to develop a product, and that all are to a large extent governed by the context in which design takes place. These assumptions have also been given support by the findings of the thesis. As demonstrated by findings three and four, the individual creative approach of designers (as determined through the types of task that they complete) does vary regardless of product, and this variance correlates significantly with the creative style of the individual. Further, as shown by the differences between experts and non-experts within study two, level of experience and expertise also influence the process that is followed, and the quality of the result. In terms of context, study three demonstrated the variance in appearance of creativity that occurs depending on the design situation and expectation of the output from the design situation. In other words, when creative behaviour is neither necessary nor beneficial, it is less likely to occur.

The thesis therefore demonstrates some level of validity of the structure of the four pillars proposed, and their benefit in aiding understanding of results. Through distinction between each pillar, rather than considering creativity as a broad and potentially ambiguous concept, creative behaviour can be identified distinction within the process completed by the designers, with understanding of the individual difference that influences its appearance, the context in which it appears, and the impact of its appearance on the design output.

11.7 Characterisation of Design Behaviour

Each study within these chapters has been aimed at the primary purpose of this thesis, the characterisation of creative behaviour within late-stage engineering design. They have employed a variety of methodological techniques, including direct observation in and out of industry, expert opinion and survey, and questionnaires. Through the studies, several characteristics of late-stage, and indeed early-stage, engineering design have been found, as have been discussed throughout this chapter.

This section summarises these findings in one place. Through the consistent study methods, comparability of studies and careful consideration of context, such findings can form a basis for much future work.

A number of common characterisations have been found, relating early-stage design, later-stage design, and the transition between the two. These are presented in Table 99 and Table 100. These are not a summation of all findings within the thesis as discussed in this section, rather those that can with confidence be stated as common characteristics. Findings relating to quality, correlation, and expert process are therefore omitted.

Table 99: Characterisations of early-stage behaviour

Section Discussed	Description
Section 11.3.1	Designers will focus on information-type tasks
Section 11.4.4	An information-type task focus will lead to higher output quality
Section 11.4.1	Designers will frequently demonstrate creative behaviour

Table 100: Characterisations of late-stage behaviour

Section Discussed	Description
Section 11.3.1	Designers will focus on application-type tasks
Section 11.4.4	An application-type task focus will lead to higher output quality
Section 11.4.1	Designers will demonstrate a higher proportion of non-creative behaviour
Section 11.4.2	Designers will typically be creative within cross-entity transformations
Section 11.4.2	Designers will demonstrate creative behaviour in different types of task, dependent on their experience and personal characteristics
Section 11.4.2	Expert designers will primarily be creative within application-type tasks; non-expert designers will be creative in both information-type and application-type tasks
Section 11.4.2	The behaviour of designers, including their creative approach, can vary between early and late stage design
Section 11.5.1	The expectation and requirements within the project will alter necessity for different types of behaviour
Section 11.5.2	Restrictions through time will increase the application-type task focus, and decrease the occurrence of creative behaviour
Section 11.5.2	Restrictions through time will increase the within-entity type tasks focus

In essence, these points describe a switch in actual behaviour between early and late-stage design, in general alignment with the change in focus of early and late stage process activities. The purpose of early-stage design of identifying functions and potential solution principles logically involves a majority of information-type tasks through research. The purpose of late-stage design to determine detailed system behaviour and structure logically involves a majority of application-type tasks.

It is the addition of understanding of the appearance of creative behaviour that provides more insight into this information. Creative behaviour itself diminishes in occurrence throughout the design process, likely as the necessity and expectation for it decreases. Into late-stage design, when few information-type tasks are required, the aim of the designer is in more incremental refinement of existing (if preliminary) structures. Their process then does not require exploration to continue, and creative behaviour decreases accordingly. When it does appear in late-stage design, creative behaviour is primarily a trait of cross-entity type tasks rather than within-entity type tasks, as the designers explore the methods of applying knowledge and taking advantage of opportunities that they have identified. Furthermore, creative behaviour will primarily manifest in application-output tasks rather than information-output tasks, the opposite to early-stage design, as the designers explore the behaviour and structure that their design will take.

Even given these trends, the possibility will always remain for the appearance of different behaviours dependent on the individual personality and experience of the designer, and the particulars of the design situation. As was stated by Rhodes (1961) and presented at the beginning of this thesis, understanding of creativity requires understanding of more than any one area; the person, their process, and their context must all be considered as contributing to the development of the product. The findings within this thesis agree with this proposal; evidence demonstrates variation in creative behaviour depending on the designer, depending on characteristics of their process (such as design stage), and depending on the design situation and context. While understanding can be deepened by research such as that presented here, variation in application will always exist dependent on the structure and understanding of each of the four pillars of creativity on a case-by-case basis.

11.7.1 Implications for Support

As summary then, late-stage design is different to early stage design in many ways, both through the situation of in which designers are working, and in the actual work of the designers. In addition to differences within literature relating to focus of design (Pahl and Beitz, 1984, Pugh, 1990, Gero, 1990), constraint profile (McGinnis and Ullman, 1990, Howard et al., 2011), and complexity (Eckert et al., 2012, Earl et al., 2005), the very behaviour of the designer under all these conditions will differ. As a complicating factor to this, there is also possibility and perhaps likelihood that behaviour will vary between designers, even in an identical design situation. An initial assertion of this thesis is therefore true – it is demonstrated that the design process varies inherently between early and late stage design, and in doing so posits the inappropriateness of consistent methods of creativity support across the whole design process.

One potential output of this work is therefore recommendations for enhanced support of designers in later-stage design situations. Based on the findings throughout Chapters Eight and Nine, there are numerous connections that can be made between behaviour types, creativity, and process. As these are based on observation rather than intervention, there is a need to study the manner in which behaviour can be influenced along each recommendation, and the actual effect of such influence in real life design processes. However, the directions for future research provided remain useful.

Within later-stage design, the designer will focus far more on the development of the design as an object, with little information searching or scoping for opportunities through research. In addition, through the study of experts this trend has been demonstrated to grow with expertise and be reinforced when under pressure. Support for designers within late-stage design must then consider this trend and act accordingly by one of two methods. Should support for the designers own process and progression towards a finished product be the goal, then the behaviour of the designer should be supported through a focus on application-type tasks and their effective completion. Should the introduction of new knowledge or progression through a more creative process be the goal, then the designer should be encouraged to complete a higher proportion of information-type tasks. The discussion of this thesis suggests several such recommendations, as summarised in Table 101, all of which require exploration and validation in further work before implementation. Further description of these suggestions is given in Section 12.2.

Table 101: Potential methods of process support

Requirement / Desire	Action to support
Quicker/more efficient design process	Encourage application-type and within-entity type tasks
More creative behaviour	Encourage cross-entity type tasks, potentially through the encouragement of information-type tasks.
Higher quality output	Encourage creative behaviour in application-type tasks
More creative output	Encourage creative behaviour in information-type tasks

11.7.2 Limitations of Study

These characterisations and recommendations are based on a collection of studies, each slightly different in structure and application. Within each, and within the methods of comparison between, there are some limitations that must be acknowledged.

The first is in sample size within the studies. Particularly in studies one and four, the number of designers was limited. In order to fully validate each finding and discussion, it would be necessary to repeat the observation and analysis completed on a higher number of participants, particularly those in industry. A higher number of participants within study three would also provide deeper understanding regarding the influence of the design situation of industry. As discussed, one implication of designer work within industry as opposed to study within academia is the role of expected process and results. Higher exposure to the varying conditions of a designer's project in industry would give broader understanding of the way in which a designer's behaviour may vary. Hence such study would inform the validity of pattern found within designer behaviour, and the potential methods of introducing designer support.

When completing this extended research, the thesis can serve as basis for understanding. Whether studies are extended directly through repetition or through comparison with the work of other researchers, the discussion within Chapter 11 can be used to form the grounding from which research continues.

The second limitation is in the impact of the variation of the methodology of each study. Although designed to be complementary, each study was different in process or design situation, and as such contains variables that reduce comparability of results. This limitation was addressed in part by consideration of the cohesion of studies presented within Section 7.5. To fully mitigate, however, an extension to study would be required in which a larger number of participants are studied for a longer period, within realistic projects from industry, and in which data collection method is consistent.

11.8 Summary: Overall Discussion

From the discussion within this chapter several common patterns within designer behaviour have been identified. These have been focused around the main aims of this thesis as a whole – characterisation of creative behaviour in late-stage design – but for the sake of comparison and completeness also consider the early-stages of design and design as a whole.

The discussion of the chapter is based upon findings presented on the subjects of the appearance of creative behaviour and approach Chapter 8, behaviour throughout the design process Chapter 9, the difference between expert and non-expert behavioural processes Chapter 10, and the role played by the particular context of industry Chapter 10. These findings in turn are the output of four studies; the first an observational study of non-expert designers, the second an observation of both non-expert and expert designers in a consistent brief, the third an analysis of quality and output creativity, and the fourth an observation of industry designers working on industrial projects.

Through careful understanding of how types of behaviour may be encouraged or discouraged, the discussion within this chapter suggests the possibility of improving the process of designers dependent on the particular context in which it occurs.

Chapter 12: Conclusions

This research has had the aim of characterisation of creative designer behaviour within the perspective of the engineering design process – particularly those tasks that occur throughout the later stages.

This has been approached through four studies, three involving separate observational studies of actual designer behaviour in differing design situations with both expert and non-expert participants; and one addressing the analysis of design quality, used to inform understanding of the behaviour to which it relates.

This chapter focuses on the major conclusions of the work with specific reference to the research aim, research questions, and research objectives set out in Chapter 5. Following, the chapter presents the implications to for both academia and industry and potential scope for future work that is has identified.

12.1 Research Aim

"TO CHARACTERISE THE CREATIVE BEHAVIOUR OF DESIGNERS WITHIN THE LATE-STAGE ENGINEERING DESIGN PROCESS"

This research has addressed the research aim through the answering of three questions, tackled through four research objectives. This section summarises the work that has been carried out through description of how each question and objective were addressed.

12.1.1 The Knowledge Gap

Through the literature review conducted and presented within Chapters Two, Three and Four, a lack of understanding of specific designer behaviour within the engineering design process was found, particularly in relation to that within the later-stages (see Section 4.5). As the human designer is at the core of engineering design and is a critical element in the production of high quality output, this presents a useful area of research. To improve the later-stage engineering by any metric, some understanding is needed of the designer within it.

The field of creativity research was used to provide structure throughout this thesis. With a focus on production of results that are original, appropriate, and surprising, the study of creativity is at its core the study of the manner in which "better" results are produced within the context of the particular design situation. The field of creativity research then provides a wealth of knowledge that can be gathered and applied to study; through the study of creative behaviour and creative output, this thesis aimed to enable understanding of how better results can be produced.

12.2 Research Objectives

Four research objectives were formulated to address the research aim, and to answer the research questions (Section 1.6). The manner in which these objectives were tackled is summarised in this section, along with main findings.

Objective One: *To identify the typical features of creative behaviour within design.*

This research objective was addressed through two methods. Initially, study through literature enabled understanding of accepted theory on creative behaviour within design and its manifestation (see Chapter 2). This theoretical understanding could then be used to formulate the framework and coding scheme and perform each study, which in turn further addressed the research objective.

Creative behaviour was determined to manifest in a process through the act of expansion (Section 2.4), based on classical creativity theory such as divergence and convergence, and classes of creative design. The creative process is considered separate to, but highly influential upon, the production of a creative output; and is a consequence of the characteristics of the designer and the design situation (see Chapter 4). Such theory was reinforced by study, with evidence of creative expansion within design, (Section 8.3), creative approach within design (Section 8.4), personal difference and influence (Section 10.2), and contextual difference (Section 10.5).

Objective Two: *To identify the typical features of the later-stage design process.*

This research objective was primarily answered through literature study, providing accepted theory and a basis on which study could be performed.

The later-stage design process is considered to be a specific design situation, discrete and separate from early-stage design or the design process in general (Chapter 3). It is identified through its focus on development of detailed system behaviour and detailed system structure (Table 8), in contrast to an early-stage focus on information and functional development (Section 11.3). Later-stage design is therefore determined by focus rather than time of occurrence or level of detail in work. The implication of this is that there is a later-stage design type of behaviour, separate from early-stage design type behaviour, and that later-stage design type behaviour can occur at many different points in time within the design process.

Later-stage design is also found to present a differing situation to the designer, both through study completed within this thesis and through literature, in such characteristics as varying focus (Howard et al., 2008a), varying constraint (McGinnis and Ullman, 1990), and varying complexity (Eckert et al., 2012) (Section 3.4 and Chapter 9). These traits reinforce the need for specific research into later-stage design behaviour, in contrast to early-stage and design in general.

Objective Three: *To investigate the appearance and integration of creative behaviour within the late-stage design process.*

This research objective was addressed through the studies completed and presented within Chapters Eight, Nine and Ten. These studies were fundamentally based on observation of designers within their design process, working on typical engineering design projects. Direct observation and analysis through the framework and coding scheme presented in Chapter 6 allowed detailed study of the focus of the actual behaviour of designers, the types of task that they completed, and their progression through the design process.

By analysis of early-stage design, late-stage design, and the design process in general, a more detailed understanding of the specifics of later-stage design could be formed (Chapters Eight and Nine). Additionally, through study of non-expert designers, expert-designers in a non-realistic setting, and expert designers working within industry, understanding of the role of design situation and context could be formed (Chapter 10).

Several characteristics of early-stage and late-stage creative and non-creative design behaviour were found (Table 102). These include such empirically derived findings as the decrease in creative behaviour as the design process continues, the differing creative approaches that can be employed, the frequent occurrence of effectuating design approaches, and the strong tendency for creative behaviour to be predominant in cross-entity type task transformations.

Of these points, that cross-entity tasks are most frequently completed in a creative manner is of particular note. Through all of the analysis completed within this work, it is this that forms the clearest pattern – of the 25 participants, only one demonstrated a higher proportion of within-entity task creative behaviour, who was also less creative overall (participant 1D, Section 8.5). With this pattern there also then comes a clear opportunity. As stated in Section 11.4, cross-entity tasks are thought to encourage creative behaviour through the lack of a conceptual link between the input to the task and the output, and are thereby more likely to require exploration. For the support of the creative behaviour of designers, this then suggests that steering towards cross-entity type tasks by prompting a designer to switch from their information input to an application output (or vice versa) may prove a viable and useful method of enhancing the creative properties of the design output.

Objective Four: *To develop understanding of the opportunities for improvement (Table 101) of creative behaviour within the late-stage design process.*

The research objective was addressed through analysis of the results of the studies completed through Chapters Eight, Nine and Ten. By the analysis of expert behavioural process set in contrast to non-expert (Section 10.2), comparison of behaviour with quality of output (Sections 8.7 and 9.7), and consideration of the role of context on design behaviour (Section 10.5), some initial recommendations can be formed for the control of later-stage design behaviour (Table 101). In truth, these recommendations form possible outputs from much discussion (Chapter 11), which identified a variety of behaviours in the scope of engineering design.

Fundamental to these are:

- The pattern of switching focus between early and late stage design and the possible reliance of this switch on experience (Section 11.3.1); in which a designer will focus less on information-type tasks and more on application-type tasks. Identified through the study of more experienced designers, this finding suggests the benefit of providing information along the thinking of experts without removing the need to develop a depth of personal experience – thereby improving the information gathering process of non-experts without removing it.
- The act of creative behaviour through the completion of cross-entity type tasks (Section 11.4.2); which presents a clear opportunity for encouragement of creative behaviour. When desired, steering designers towards cross-entity tasks has significant potential to increase the occurrence of creative tasks, and hence increase the likelihood of producing a creative output.
- The potential streamlining of the design process under pressurised design conditions (Section 11.5.2); in which designers complete a higher proportion of information-type tasks and within-entity type tasks when a higher rate of working is required. Steering designers towards such tasks may then have the effect of decreasing the time taken to produce a design output.
- The steering of design output based on altering focus onto different types of task (Section 11.4.4). When a higher quality output is desired, evidence suggests that creative behaviour in application-type tasks should be encouraged. When a more creative output is desired, evidence suggests that creative behaviour in information-type tasks should be encouraged. When the designer is aware of the form that they wish their output to take based on specific circumstances and requirements, there is then scope for them to actively steer their process towards it based on the types of task that they complete.

By providing a basis of understanding of later-stage design behaviour within engineering design, this thesis gives direction to future research studying the actual effect of altering design behaviour according to the patterns and trends discovered.

12.3 Research Questions

The four research objectives were formulated to inform answers to the three research questions, which bear many similarities. These research questions and the manner in which they were answered are presented here.

RQ1: What are the characteristics of creative behaviour?

This research question was addressed primarily through research objective one. From literature this highlighted theoretical commonalities in the appearance of creative behaviour, such as through characteristics of the designer and the design situation (see Section 4.4). From initial study, this highlighted such characteristics as creative approach (in which a designer will focus on certain types of creative behaviour, correlating with their personal creative style, see Section 10.2).

Fundamental to all creative behaviour in design is the act of *expansion*, indicated by divergence and creative convergence (Section 2.4). It is through expansion that a designer will explore and discover new opportunities that can be applied to their design solution, and hence through expansion that the developments that produce a creative output are found. Within (Section 2.4) different classes of creative design were also presented, which in turn led to the understanding that forms the basis for the framework and coding scheme used within this thesis. Within design, creative behaviour can focus either on the knowledge and variables available for use in the design process, or on the way in which the available knowledge and variables are used. It is therefore expansion in these two distinct-but-related areas that lead to creative output.

Through the understanding gained of creative behaviour and the study of the field of creativity, the research framework and coding scheme were developed, thereby forming the core of research within this thesis.

RQ2: How does creative behaviour manifest within the late-stage design process?

The question was addressed through research objectives one, two, and three. Through a combination of empirical studies, a characterisation of patterns in designer behaviour was formed particular to later-stage design and to the design process in general. These empirical studies were all based upon observation of designer’s actions within a variety of design projects and design situations, and were analysed using the framework and coding scheme developed as an output to RQ1. Characterisation of later-stage creative designer behaviour was found to be, at least in part, dependent on design context and individual participant. Commonalities in characterisation are outlined as in Table 102, re-iterated from the discussion throughout Chapter 11.

This combinatory approach allowed deeper understanding than purely focused study, and used the advantages of contrast between experts and non-experts, observational study and ethnographic study to form confidence in findings.

RQ3: What are the opportunities for designer support in later-stage engineering design?

This research question was addressed by research objective four. The numerous findings and characterisations presented throughout the latter half of this thesis present opportunities both for designer support, and for future research. With the knowledge of typical and individual designer behaviour within later-stage design provided by this thesis, and the knowledge that behaviour can alter based on design situation and influences upon the designer, there is great potential to investigate methods of improving design process output.

Briefly summarised in Table 101, these include streamlining the design process through a focus on application-type and within-entity type tasks when a high rate of working is desired; encouraging creative behaviour through the encouragement of cross-entity type tasks in later-stage design; increasing output quality through the encouragement of an effectuating approach in later-stage design, and increasing output creativity through the encouragement of an astute approach in later-stage design.

Further, through the identification of such potential methods of improvement and the detailed exploration that has occurred throughout this work, valid and useful directions for focused future work have been presented (as summarised in Section 12.5).

Table 102: Characterisations of designer behaviour

Early-stage Characterisation	
Section Discussed	**Description**
Section 11.3.1	Designers will focus on information-type tasks
Section 11.4.4	An information-type task focus will lead to higher output quality
Section 11.4.1	Designers will frequently demonstrate creative behaviour
Late-stage Characterisation	
Section 11.3.1	Designers will focus on application-type tasks
Section 11.4.4	An application-type task focus will lead to higher output quality
Section 11.4.1	Designers will demonstrate a higher proportion of non-creative behaviour
Section 11.4.2	Designers will typically be creative within cross-entity transformations
Section 11.4.2	Designers will demonstrate creative behaviour in different types of task, dependent on their experience and personal characteristics
Section 11.4.2	Expert designers will primarily be creative within application-type tasks; non-expert designers will be creative in both information-type and application-type tasks
Section 11.4.2	The behaviour of designers, including their creative approach, can vary between early and late stage design
Section 11.5.1	The expectation and requirements within the project will alter necessity for different types of behaviour
Section 11.5.2	Restrictions through time will increase the application-type task focus, and decrease the occurrence of creative behaviour
Section 11.5.2	Restrictions through time will increase the within-entity type tasks focus

12.4 Implications

The implications from this work can be considered as two-fold, those that impact academia directly, and those that impact industry.

12.4.1 Implications within Academia

Due to the nature of the thesis as presentation of exploratory grounding, there are many opportunities for further work, as will be summarised in Section 12.5. These have been developed through the process of addressing research objective four and research question three.

In application, the work within this thesis presents a core of understanding of the behaviour of designers within the later-stages of the engineering design process, and also an example of a broadly applicable methodology by which they can be studied. This has been completed through amalgamation of the research fields of creativity, engineering design, and designer behaviour.

Primary implications of this work within an academic context are therefore a clear extension to the research aim – directions for future research into the improvement of designer behaviour within later-stage design, with the aim of improving the design output. For example, while several potential opportunities for designer support have been presented (see Section 12.2 and Table 101), there is little evidence of *how* each opportunity may be achieved. A higher proportion of cross-entity tasks may increase the potential for creative tasks to occur, but it is not known how cross-entity tasks may be encouraged. Similarly, steering designers towards application-type tasks and within-entity type tasks may have potential to streamline towards a higher rate of working, but it is not known how this could be effectively and appropriately be achieved.

It is from the basic understanding and patterns identified in this thesis that such work can be performed with potential for significant benefit. Through the contribution to knowledge within the fields of designer behaviour and expertise, the design process, and creativity; there is broad scope in academic circles to complete focused and useful research, leading to the knowledge to produce useful and appropriate methods of support and creative support in later-stage design.

12.4.2 Implications within Industry

Within industry, the scope of this work must be viewed as of more eventual benefit, and as a continuation to academic work as described. The direct improvement of output in a manner compatible with individual designers within their process is of clear benefit within an industry context. Where quality of output to a large extent determines market success, and the minimisation of costs influences profit, processes by which such factors can be improved are valuable.

Implication within industry must then lie in application of the findings of this thesis on the future work performed within academia. Detailed understanding of characteristics of creative behaviour within later-stage design has significant potential to lead to the manner in which later-stage design can be supported and controlled, or the manner in which designers can be effectively trained; both of which form active and progressive methods of improving industrial process output. For example, when industry requires an output from a design process that is of a particularly creative form, such as when solution methods have stagnated and a step-change is required, designers could be encouraged to complete a higher proportion of creative information-type tasks in later-stage design. Similarly, when under difficult restrictions in terms of time and potentially budget, encouraging application-type and within-entity type tasks could reduce time taken and costs associated with exploration.

Following further understanding gained from study of actual intervention and manipulation of designers process within later-stage design, this work provides grounding that can inform and lead to appropriate and useful methods of support.

12.5 Future work

This thesis alludes to much further work by its nature, for the exploration of methods of support based on the understanding of later-stage creative designer behaviour. Further to these, however, there are interesting areas for research that this work has suggested, but towards which has made less contribution.

The Effect of Manipulation of Designer Process

As has been stated, primary in future work is the study of the actual effect of steering a designer's process towards the directions that this thesis suggests. While clear patterns have been found that link to and suggest potential benefit, it is not directly known how these patterns can effectively be encouraged to appear, or the actual effect of intervention on the designer's process and output. Relating directly to the results of this thesis, numerous questions can be formed:

> *How can the process of a designer be effectively and appropriately steered towards the characteristics identified within this thesis?*
>
> *What would be the actual effect of intervention and support towards such characteristics?*
>
> *Considering the role of individuality in creative behaviour, do methods of support need to account for the individual approaches of each designer in order to be broadly useful and applicable?*

It is through addressing such questions that potential implications from this thesis can be achieved in industry.

The Quality of Creative Behaviour

At its current state, the research framework makes no distinction against what could be termed *quality* of creative behaviour. As implied by discussion on creative level, there is scope for study of the manner of creative acts and their impact on the extent of expansion. For example, in cases where little expansion occurs but the result is highly creative or of exceptional quality, what are the contributing factors of designer behaviour or context? Conversely, when a designer completes substantial explorative behaviour but the results are of lower quality or creativity, what are the causal factors? Answers to such questions would give deeper understanding of the *effect* of creative behaviour, beyond its simple occurrence.

The Cognitive Strategies Employed within Creative Designer Behaviours

Another avenue for research is into the cognitive strategies employed by designers within their behaviour. This level of granularity and detail was considered beyond scope within this thesis, which aimed to understand *what* a designer will do before trying to understand *why* they do it. Following detailed understanding of *what*, however, the cognitive level can now be approached in detail. This would provide understanding of the detailed solution strategies of experts and their thinking processes within each task and activity, and give further insight into the way in which creative behaviour appears, and potential methods of designer support.

The Classification and Study of the Role of Project Context on Design Behaviour

A further area for research is that proposed through Chapter 10. Design context has been demonstrated to influence designer behaviour through the conditions and expectations of their working. There is currently little by way of detailed classification of these influences. Such a method of understanding could include influence placed upon designers by their brief, working environment, team, use of tools, time, budget, among many other factors. The output of this understanding would then allow more detailed analysis of results within the perspective of this thesis, but also be applicable beyond through measured comparison with the work of other researchers and comparison of the differences between expert and non-expert design situations.

12.6 Contribution to Knowledge

The primary contribution to knowledge from this thesis is in deeper understanding of designer behaviour within later-stage design. Specifically, this thesis has identified several characteristics of creative designer behaviour in later-stage design, such as that designers will follow one of two creative approaches (correlating with their creative style)(Snider et al., 2013a) and that these approaches are a feature of the designer rather than the brief (Snider et al., 2014); that certain types of task will indicate a higher occurrence of creative behaviour; and suggestions of a connection between types of task completed creatively and design output quality. Following a fundamental theme within this work, these are set in contrast to early-stage design and the general design process for the purpose of comparison, allowing more detailed knowledge of similarity, difference and the effect of each.

The framework and coding scheme employed throughout each study demonstrate a newly developed method of analysis, including the feasibility of the direct study of designer behaviour within their actual process, using findings to inform understanding of the person, their production of an output, and their working context. As published in Snider et al. (2013a), the framework and coding scheme allow detailed analysis of the process of a designer on a task-by-task basis, the identification of creative tasks, and the identification of design stage at which work is occurring. Through these combined streams of analysis, and as are presented in this thesis, detailed findings of creative designer behaviour (as defined through the summation of their tasks), can be formed.

Finally, the combinatory study approach employed within the work has provided the opportunity to develop findings concerning both creative and non-creative designer behaviour across appropriate later-stage design situations, additionally presenting some relationships of designer behaviour to expertise and to design situation. A combination of the use of longer term and short term studies, involving both a mix of projects in one study, and identical projects in the another; has led to confidence that results are applicable in a broader sense than their individual studies, and are hence representative of design and the design process in a wider (but still appropriate) context. The use of both expert and non-expert participants has led to findings involving differences in task occurrence relating to expertise, such as a lower information-type task occurrence in later-stage design and a higher creative task occurrence when studying the processes of experts.

Through the four studies performed and presented within this thesis, several characterisations of creative behaviour in the later-stage engineering design process have been identified. Through the understanding that these create, this thesis creates significant scope for future research that has potential to provide useful methods of designer support, appropriate to their design situation and the context of later-stage engineering design.

12.7 Publications

The following papers have been published as an output of work completed within this thesis.

Journal

Snider, C. M., Dekoninck, E. A., & Culley, S. J. (2014). The appearance of creative behavior in later stage design processes. International Journal of Design Creativity and Innovation, 2, 1-19.

Snider, C. M., Culley, S. J., & Dekoninck, E. A. (2013). Analysing creative behaviour in the later stage design process. Design Studies, 34, 543-574.

Conference

Snider, C. M., Dekoninck, E. A., & Culley, S. J. (2014). A study of creative behaviour in the early and late stage design process. In DESIGN 2014: The 13th International Design Conference. Dubrovnik, Croatia.

Snider, C. M., Culley, S. J., & Dekoninck, E. A. (2013). Determining relative quality for the study of creative design output. In ICoRD'13: International Conference on Research into Design. Chennai, India.

Snider, C. M., Cash, P. J., Dekoninck, E. A., & Culley, S. J. (2012). Variation in creative behaviour during the later stages of the design process. In ICDC2012: The 2nd International Conference on Design Creativity. Glasgow, Scotland.

Snider, C. M., Dekoninck, E. A., & Culley, S. J. (2012). Improving confidence in smaller data sets through methodology: The development of a coding scheme. In DESIGN 2012: The 12th International Design Conference. Dubrovnik, Croatia.

Snider, C. M., Dekoninck, E. A., & Culley, S. J. (2011). Studying the appearance and effect of creativity within the latter stages of the product development process. In DESIRE'11: The 2nd International Conference on Creativity and Innovation in Design. Eindhoven, Netherlands.

Snider, C. M., Dekoninck, E. A., Yue, H., & Howard, T. J. (2011). Analyzing the Use of Four Creativity Tools in a Constrained Design Situation. In ICED11: The 18th International Conference on Engineering Design. Copenhagen, Denmark.

12.8 References

ABERNATHY, W. J. & UTTERBACK, J. M. 1978. Patterns of industrial innovation. *Journal Title: Technology review. Ariel,* 64**,** 254.28.

ADLER, P. S. & OBSTFELD, D. 2007. The role of affect in creative projects and exploratory search. *Industrial and Corporate Change,* 16**,** 19.

AGOGUE, M., KAZAKCI, A., WEIL, B. & CASSOTTI, M. 2011. The impact of examples on creative design: explaining fixation and stimulation effects. *ICED'11: International conference on engineering design.* Copenhagen, Denmark.

AHMED, S., WALLACE, K. M. & BLESSING, L. T. 2003. Understanding the differences between how novice and experienced designers approach design tasks. *Research in engineering design,* 14**,** 1-11.

AKIN, Ö. & AKIN, C. 1996. Frames of reference in architectural design: analysing the hyperacclamation (Aha-!). *Design Studies,* 17**,** 341-361.

ALTSHULLER, G. & RODMAN, S. 1999. *The innovation algorithm: TRIZ, systematic innovation and technical creativity,* Worcester, MA, Technical Innovation Center.

AMABILE, T. 1996. *Creativity in context,* Boulder, CO, Westview Press.

AMABILE, T. M. 1982a. Children's Artistic Creativity. *Personality and Social Psychology Bulletin,* 8**,** 573.

AMABILE, T. M. 1982b. Social psychology of creativity: A consensual assessment technique. *Journal of personality and social psychology,* 43**,** 997-1013.

AMABILE, T. M., CONTI, R., COON, H., LAZENBY, J. & HERRON, M. 1996. Assessing the Work Environment for Creativity. *The Academy of Management Journal,* 39**,** 1154-1184.

ANDERSON, H. H. 1959. *Creativity and its Cultivation*, Harper & Row.

ANDREWS, F. M. & FARRIS, G. F. 1972. Time pressure and performance of scientists and engineers: A five-year panel study. *Organizational Behavior and Human Performance,* 8**,** 185-200.

ANON. 2012. *Reflections from Coller IP on the ongoing court battles around mobile technology* [Online]. London, UK: Coller IP. Available: http://www.colleripmanagement.com/news/mobile-phone-innovation-wars [Accessed 29/11/2013 2013].

ANTONSSON, E. K. & CAGAN, J. 2001. *Formal engineering design synthesis,* Cambridge, Cambridge University Press.

ATMAN, C. J., CHIMKA, J. R., BURSIC, K. M. & NACHTMANN, H. L. 1999. A comparison of freshman and senior engineering design processes. *Design Studies,* 20**,** 131-152.

BALL, L. J. & ORMEROD, T. C. 1995. Structured and opportunistic processing in design: A critical discussion. *International Journal of Human-Computer Studies,* 43**,** 131-151.

BALL, L. J., ST. B. T. EVANS, J., DENNIS, I. & ORMEROD, T. C. 1997. Problem-solving Strategies and Expertise in Engineering Design. *Thinking & Reasoning,* 3**,** 247-270.

BARRICK, M. R., STEWART, G. L., NEUBERT, M. J. & MOUNT, M. K. 1998. Relating Member Ability and Personality to Work-Team Processes and Team Effectiveness. *Journal of Applied Psychology,* 83**,** 377-391.

BARRON, F. 1963. *Creativity and psychological health,* Princeton, NJ, Van Nostrand.

BARRON, F. & HARRINGTON, D. M. 1981. Creativity, intelligence, and personality. *Annual review of psychology,* 32**,** 439-476.

BARTON, J. A., LOVE, D. M. & TAYLOR, G. D. 2001. Design determines 70% of cost? A review of implications for design evaluation. *Journal of Engineering Design,* 12**,** 47-58.

BASADUR, M. & GELADE, G. 2003. Using the creative problem solving profile (CPSP) for diagnosing and solving real-world problems. *Emergence,* 5**,** 22-47.

BENAMI, O., JIN, Y. 2002. Creative Simulation in Conceptual Design. *DETC '02: ASME 2002 Design Engineering Technical Conferences.* Montreal, Canada.

BENDER, B. & BLESSING, L. 2004. On the Superiority of Opportunistic Design Strategies during Early Embodiment Design. *DESIGN 2004: The 8th International Design Conference.* Dubrovnik, Croatia.

BERENDS, H., REYMEN, I., STULTIËNS, R. G. L. & PEUTZ, M. 2011. External designers in product design processes of small manufacturing firms. *Design Studies,* 32**,** 86-108.

BILTON, C. 2007. *Management and creativity: from creative industries to creative management*, Blackwell Pub.

BJÖRKLUND, T. A. 2013. Initial mental representations of design problems: Differences between experts and novices. *Design Studies,* 34**,** 135-160.
BLANCHARD, B. S., FABRYCKY, W. J. & FABRYCKY, W. J. 1990. *Systems engineering and analysis*, Prentice Hall Englewood Cliffs, New Jersey.
BLESSING, L. & CHAKRABARTI, A. 2009. *DRM, a Design Research Methodology,* New York, Springer.
BODEN, M. 2004. *The creative mind: Myths and mechanisms*, Routledge.
BODEN, M. A. 1994. What is Creativity? *In:* BODEN, M. A. (ed.) *Dimensions of Creativity.* Cambridge, MA: MIT Press.
BOHM, D. & PEAT, F. D. 2010. *Science, order and creativity*, Taylor and Francis US.
BONNER, S. E. & LEWIS, B. L. 1990. Determinants of Auditor Expertise. *Journal of Accounting Research,* 28**,** 1-20.
BRIGGS, R. O. 2006. On theory-driven design and deployment of collaboration systems. *International Journal of Human-Computer Studies,* 64**,** 573-582.
BRINKOP, A., LAUDWEIN, N. & MAASEN, R. 1995. Routine design for mechanical engineering. *AI Magazine,* 16**,** 74-85.
BROWN, D. C. 1996. Routineness revisited. *In:* WALDRON, M. & WALDRON, K. (eds.) *Mechanical Design: Theory and Methodology.* Springer-Verlag.
BROWN, D. C. 2012. Creativity, surprise & design: an introduction and investigation. *In:* DUFFY, A., NAGAI, Y. & TAURA, T. (eds.) *ICDC2012: 2nd International conference on design creativity.* Glasgow, UK: The Design Society.
BRUNER, J. S. 1967. The conditions of creativity. *In:* GRUBER, H. E. (ed.) *Contemporary approaches to creative thinking.* Atherton Press.
BRYMAN, A. 2012. *Social research methods*, Oxford university press.
BUDYNAS, R. G., NISBETT, J. KEITH 2008. *Shigley's mechanical engineering design,* London, McGraw-Hill.
CANDY, L. & EDMONDS, E. A. 1997. Supporting the creative user: a criteria-based approach to interaction design. *Design Studies,* 18**,** 185-194.
CARAYANNIS, E. & COLEMAN, J. 2005. Creative system design methodologies: the case of complex technical systems. *Technovation,* 25**,** 831-840.
CARSON, D. K. 1999. Counseling. *In:* RUNCO, M. A. & PRITZKER, S. R. (eds.) *Encyclopedia of creativity, Volume 1.* Elsevier.
CASH, P. J., HICKS, B. J. & CULLEY, S. J. 2013. A comparison of designer activity using core design situations in the laboratory and practice. *Design Studies,* 34**,** 575-611.
CHAKRABARTI, A. 2006. Defining and supporting design creativity. *Design 2006: The 9th International Design Conference.* Dubrovnik, Croatia.
CHAKRABARTI, A., BLIGH, T. P. & HOLDEN, T. 1992. Towards a decision-support framework for the embodiment phase of mechanical design. *Artificial Intelligence in Engineering,* 7**,** 21-36.
CHAKRABARTI, A. & KHADILKAR, P. 2003. A measure for assessing product novelty. *ICED 03: The 14th International Conference on Engineering Design.* Stockholm, Sweden.
CHAN, J., FU, K., SCHUNN, C., CAGAN, J., WOOD, K. & KOTOVSKY, K. 2011. On the benefits and pitfalls of analogies for innovative design: Ideation performance based on analogical distance, commonness, and modality of examples. *Journal of Mechanical Design,* 133.
CHENOUARD, R., GRANVILLIERS, L. & SEBASTIAN, P. 2009. Search heuristics for constraint-aided embodiment design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM,* 23**,** 175-195.
CHI, M. T. H. 2006. Two approaches to the study of experts' characteristics. *In:* ERICSSON, K. A., CHARNESS, N., FELTOVICH, P. J. & HOFFMAN, R. R. (eds.) *The Cambridge handbook of expertise and expert performance.* Cambridge, UK: Cambridge University Press.
CHRISTIAANS, H. & VENSELAAR, K. 2005. Creativity in design engineering and the role of knowledge: Modelling the expert. *International Journal of Technology and Design Education,* 15**,** 217-236.
CHRYSIKOU, E. G. & WEISBERG, R. W. 2005. Following the Wrong Footsteps: Fixation Effects of Pictorial Examples in a Design Problem-Solving Task. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* 31**,** 1134.
CLARK, K. B. 1989. Project scope and project performance: The effect of parts strategy and supplier involvement on product development. *Management Science,* 35**,** 1247-1263.
COHEN, J. 1960. A coefficient of agreement for nominal scales. *Educational and psychological measurement,* 20**,** 37-46.

COLLINS, M. A. & AMABILE, T. 1999. Motivation and creativity. *In:* STERNBERG, R. J. (ed.) *Handbook of Creativity.* New York: Cambridge University Press.
COLLINS, P., SHUKLA, S. & REDMILES, D. 2002. Activity theory and system design: A view from the trenches. *Computer Supported Cooperative Work (CSCW),* 11**,** 55-80.
COUGER, J. D. 1990. Ensuring Creative Approaches in Information System Design. *Managerial and Decision Economics,* 11**,** 281-295.
CRAMOND, B., MATTHEWS-MORGAN, J., BANDALOS, D. & ZUO, L. 2005. A report on the 40-year follow-up of the Torrance Tests of Creative Thinking: Alive and well in the new millennium. *Gifted Child Quarterly,* 49**,** 283.
CROPLEY, A. 2006. In Praise of Convergent Thinking. *Creativity Research Journal,* 18**,** 391-404.
CROSS, N. 1997. Descriptive models of creative design: application to an example. *Design Studies,* 18**,** 427-440.
CROSS, N. 2000. *Engineering Design Methods - Strategies for Product Design (3rd Edition),* Chichester, John Wiley & Sons.
CROSS, N. 2001. Design cognition: Results from protocol and other empirical studies of design activity. *Design knowing and learning: Cognition in design education***,** 79-103.
CROSS, N. 2004a. Creative Thinking by Expert Designers. *The Journal of Design Research,* 4.
CROSS, N. 2004b. Expertise in design: an overview. *Design Studies,* 25**,** 427-441.
CROSS, N. & CROSS, A. C. 1998. Expertise in engineering design. *Research in engineering design,* 10**,** 141-149.
CSIKSZENTMIHALYI, M. 1999. Implications of a systems perspective for the study of creativity. *In:* STERNBERG, R. J. (ed.) *Handbook of Creativity.* New York: Cambridge University Press.
CURRANO, R. & LEIFER, L. 2009. Understanding idealogging: The use and perception of logbooks within a capstone engineering design course. *ICED'09: International Conference on Engineering Design.* Stanford, CA, USA.
DAVIS, T. R. V. 1984. The Influence of the Physical Environment in Offices. *Academy of Management Review,* 9**,** 271-283.
DE GROOT, A. D. 1978. *Thought and choice in chess*, Walter de Gruyter.
DE JONG, T. 2010. Cognitive load theory, educational research, and instructional design: some food for thought. *Instructional Science,* 38**,** 105-134.
DEMIRKAN, H. & AFACAN, Y. 2012. Assessing creativity in design education: Analysis of creativity factors in the first-year design studio. *Design Studies,* 33**,** 262-278.
DEWAR, R. D. & DUTTON, J. E. 1986. The Adoption of Radical and Incremental Innovations: An Empirical Analysis. *Management Science,* 32**,** 1422-1433.
DIETER, G. E. & SCHMIDT, L. C. 2009. *Engineering Design,* Boston, MA, McGraw-Hill.
DIXON, J. R. 1966. *Design engineering: Inventiveness, analysis, and decision making,* New York, McGraw-Hill.
DORST, K. 2003. The problem of design problems. *Expertise in design***,** 135-147.
DORST, K. 2006. Design problems and design paradoxes. *Design issues,* 22**,** 4-17.
DORST, K. & CROSS, N. 2001. Creativity in the design process: co-evolution of problem-solution. *Design Studies,* 22**,** 425-437.
DYM, C. L. 1994. *Engineering Design: A Synthesis of Views,* Cambridge, Cambridge University Press.
DYM, C. L., AGOGINO, A. M., ERIS, O., FREY, D. D. & LEIFER, L. J. 2005. Engineering design thinking, teaching, and learning. *Journal of Engineering Education,* 94**,** 103-120.
EARL, C., ECKERT, C. & CLARKSON, J. 2005. Design Change and Complexity. *2nd Workshop on Complexity in Design and Engineering.* Glasgow, Scotland.
ECKERT, C., CLARKSON, P. J. & ZANKER, W. 2004. Change and customisation in complex engineering domains. *Research in engineering design,* 15**,** 1-21.
ECKERT, C., STACEY, M., WYATT, D. & GARTHWAITE, P. 2012. Change as little as possible: creativity in design by modification. *Journal of Engineering Design,* 23**,** 337-360.
ECKERT, C., WYATT, D. & CLARKSON, P. 2009. The elusive act of synthesis: creativity in the conceptual design of complex engineering products. *Creativity and Cognition 2009.* Berkeley, CA: ACM.
EINSTEIN, A. 1982. How I created the theory of relativity. *Physics Today,* 35.
EISENBERGER, R. & SHANOCK, L. 2003. Rewards, Intrinsic Motivation, and Creativity: A Case Study of Conceptual and Methodological Isolation. *Creativity Research Journal,* 15**,** 121-130.
EISENTRAUT, R. 1997. Individual styles of problem solving and their relation to representations in the design process. *Design Studies,* 18**,** 369-383.

ELO, S. & KYNGÄS, H. 2008. The qualitative content analysis process. *Journal of advanced nursing,* 62**,** 107-115.

EP 2009. Regulation (EC) No 443/2009 of the European Parliament and of the Council of 23 April 2009 setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO 2 emissions from light-duty vehicles. *In:* PARLIAMENT, E. (ed.).

ERICSSON, K. A. 1996. The aquisition of expert performance: An introduction to some issues. *In:* ERICSSON, K. A. (ed.) *The road to excellence: The aquisition of expert performance in the arts and sciences, sports and games.* Mahwah, N.J.: Erlbaum.

ERICSSON, K. A., KRAMPE, R. T. & TESCH-RÖMER, C. 1993. The role of deliberate practice in the acquisition of expert performance. *Psychological Review,* 100**,** 363-406.

ERICSSON, K. A. & LEHMANN, A. C. 1996. Expert and exceptional performance: Evidence of maximal adaptation to task constraints. *Annual review of psychology,* 47**,** 273-305.

EYSENCK, H. J. 1973. IQ, social class and educational policy. *Change***,** 38-42.

EYSENCK, H. J. 1994. The Measurement of creativity. *In:* BODEN, M. A. (ed.) *Dimensions of Creativity.* Cambridge, MA.: MIT Press.

FEIST, G. J. 1999. The influence of personality on artistic and scientific creativity. *In:* STERNBERG, R. J. (ed.) *Handbook of Creativity.* New York: Cambridge University Press.

FEIST, G. J. & BARRON, F. X. 2003. Predicting creativity from early to late adulthood: Intellect, potential, and personality. *Journal of Research in Personality,* 37**,** 62-88.

FENG, C.-X., HUANG, C.-C., KUSIAK, A. & LI, P.-G. 1996. Representation of functions and features in detail design. *Computer-Aided Design,* 28**,** 961-971.

FINGER, S. 1989a. A review of research in mechanical engineering design. Part I: Descriptive, prescriptive, and computer-based models of design processes. *Research in engineering design,* 1**,** 51.

FINGER, S. 1989b. A review of research in mechanical engineering design. Part II: Representations, analysis, and design for the life cycle. *Research in engineering design,* 1**,** 121.

FINKE, R. A. 1990. *Creative imagery: Discoveries and inventions in visualization*, L. Erlbaum Associates.

FINKE, R. A. 1995. Creative insight and preinventive forms. *In:* STERNBERG, R. J. & DAVIDSON, J. E. (eds.) *The Nature of Insight.* MIT Press.

FINKE, R. A., WARD, T. B., SMITH, S. M. 1996. *Creative Cognition: Theory, Research and Applications,* Cambridge, Mass, MIT Press.

FRENCH, M. J. 1971. *Engineering Design: the conceptual stage,* London, Heinemann Educational.

FRICKE, G. 1996. Successful individual approaches in engineering design. *Research in engineering design,* 8**,** 151-165.

FRIEDMAN, K. 2003. Theory construction in design research: criteria: approaches, and methods. *Design Studies,* 24**,** 507-522.

GARVIN, D. A. 1987. Competing on the eight dimensions of quality. *Harvard Business Review,* 65**,** 101-109.

GE, X. & LAND, S. M. 2004. A conceptual framework for scaffolding III-structured problem-solving processes using question prompts and peer interactions. *Educational Technology Research and Development,* 52**,** 5-22.

GERO, J. S. 1990. Design Prototypes: A Knowledge Representation Schema for Design. *AI Magazine.*

GERO, J. S. 1996. Creativity, emergence and evolution in design. *Knowledge-Based Systems,* 9**,** 435-448.

GERO, J. S. 1998. Conceptual designing as a sequence of situated acts. *Artificial intelligence in structural engineering.* Springer.

GERO, J. S. 2000. Computational models of innovative and creative design processes. *Technological Forecasting and Social Change,* 64**,** 183-196.

GERO, J. S. & KANNENGIESSER, U. 2004. The situated function-behaviour-structure framework. *Design Studies,* 25**,** 373-391.

GERO, J. S. & TANG, H. H. 2001. The differences between retrospective and concurrent protocols in revealing the process-oriented aspects of the design process. *Design Studies,* 22**,** 283-295.

GETZELS, J. W. & JACKSON, P. W. 1962. *Creativity and intelligence*, Wiley New York.

GOEL, A. K. 1997. Design, analogy, and creativity. *IEEE expert,* 12**,** 62-70.

GOEL, V. & PIROLLI, P. 1992. The structure of design problem spaces. *Cognitive Science,* 16**,** 395-429.

GOLDSCHMIDT, G. 1994. On visual design thinking: the vis kids of architecture. *Design Studies,* 15**,** 158-174.

GOLDSMITH, R. E. & MATHERLY, T. A. 1987. Adaption-innovation and creativity: A replication and extension. *British Journal of Social Psychology,* 26**,** 79-82.

GONCHER, A., JOHRI, A., KOTHANETH, S. & LOHANI, V. 2009. Exploration and exploitation in engineering design: Examining the effects of prior knowledge on creativity and ideation. *39th ASEE/IEEE Frontiers in Education Conference.* San Antonia, TX: IEEE.

GUILFORD, J. P. 1950. Creativity research: Past, present and future. *American psychologist,* 5**,** 444-454.

GUILFORD, J. P. 1956. The structure of intellect. *Psychological Bulletin,* 53**,** 267-293.

GUILFORD, J. P. 1968. *Intelligence, Creativity and Their Educational Implications*, Knapp.

GUINDON, R. 1990. Designing the design process: exploiting opportunistic thoughts. *Human-Computer Interaction,* 5**,** 305-344.

GUPTA, S. K., CHEN, Y., FENG, S. & SRIRAM, R. 2003. A system for generating process and material selection advice during embodiment design of mechanical components. *Journal of Manufacturing Systems,* 22**,** 28-45.

GUZZO, R. A. & DICKSON, M. W. 1996. TEAMS IN ORGANIZATIONS: Recent Research on Performance and Effectiveness. *Annual Review of Psychology,* 47**,** 307-338.

HALES, C. 1986. *Analysis of the Engineering Design Process in an Industrial Context.* PhD, University of Cambridge.

HALES, C. 1987. *Analysis of the Engineering Design Process in an Industrial Context,* Cambridge, University of Cambridge.

HARRISON, S. & DOURISH, P. 1996. Re-place-ing space: the roles of place and space in collaborative systems. *Proceedings of the 1996 ACM conference on Computer supported cooperative work.* Boston, MA: ACM.

HATCHUEL, A. & WEIL, B. 2003. A New Approach of Innovative Design: An Introduction to C-K Theory. *ICED03: The 14th International Conference on Engineering Design.* Stockholm, Sweden.

HAYES-ROTH, B. & HAYES-ROTH, F. 1979. A cognitive model of planning. *Cognitive Science,* 3**,** 275-310.

HAYES, A. F. & KRIPPENDORFF, K. 2007. Answering the call for a standard reliability measure for coding data. *Communication Methods and Measures,* 1**,** 77-89.

HAYES, J. R. 1989. Cognitive processes in creativity. *In:* GLOVER, J. A., RONNING, R. R. & REYNOLDS, C. R. (eds.) *Handbook of creativity.* Springer.

HELSON, R. & CRUTCHFIELD, R. S. 1970. Mathematicians: The creative researcher and the average PhD. *Journal of Consulting and Clinical Psychology,* 34**,** 250-257.

HELSON, R. & PALS, J. L. 2000. Creative potential, creative achievement, and personal growth. *Journal of Personality,* 68**,** 1-27.

HIRTZ, J., STONE, R. B., MCADAMS, D. A., SZYKMAN, S. & WOOD, K. L. 2002. A functional basis for engineering design: reconciling and evolving previous efforts. *Research in engineering design,* 13**,** 65-82.

HO, C. H. 2001. Some phenomena of problem decomposition strategy for design thinking: differences between novices and experts. *Design Studies,* 22**,** 27-45.

HOLYOAK, K. J. 1991. Symbolic connectionism: toward third-generation theories of expertise. *In:* ERICSSON, K. A., SMITH, J. (ed.) *Toward a general theory of expertise: prospects and limits.* Cambridge: Cambridge University Press.

HORVATH, I. 2004. A treatise on order in engineering design research. *Research in Engineering Design,* 15**,** 155-181.

HOWARD, T. J., CULLEY, S. J. & DEKONINCK, E. A. 2006. Information as an input into the creative process. *DESIGN 2006: The 9th International Design Conference.* Dubrovnik, Croatia.

HOWARD, T. J., CULLEY, S. J. & DEKONINCK, E. A. 2008a. Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies,* 29**,** 160-180.

HOWARD, T. J., CULLEY, S. J. & DEKONINCK, E. A. 2008b. Idea generation in conceptual design. *In:* MARJANOVIC, D., STORGA, M., PAVKOVIC, N. & BOJCETIC, N. (eds.) *DESIGN 2008: 10th International Design Conference.* Dubrovnik, Croatia.

HOWARD, T. J., CULLEY, S. J. & DEKONINCK, E. A. 2009. The Integration of Systems Levels and Design Activities to Position Creativity Support Tools. *ICoRD '09: International Conference on Research into Design.* Bangalore, India.

HOWARD, T. J., DEKONINCK, E. A. & CULLEY, S. J. 2010. The use of creative stimuli at early stages of industrial product innovation. *Research in Engineering Design,* 21**,** 263-274.

HOWARD, T. J., NAIR, V. V., CULLEY, S. J. & DEKONINCK, E. A. 2011. The Propagation and Evolution of Design Constraints: A Case Study. *ICoRD '11: International Conference on Research into Design.* Bangalore, India.

HUANG, C. C. & KUSIAK, A. 1998. Modularity in design of products and systems. *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on,* 28**,** 66-77.

ICHNIOWSKI, C., KOCHAN, T. A., LEVINE, D., OLSON, C. & STRAUSS, G. 1996. What works at work: Overview and assessment. *Industrial Relations,* 35**,** 299.

ISAKSEN, S. G. & PUCCIO, G. J. 1988. Adaption-innovation and the Torrance Tests of Creative Thinking: The level-style issue revisited. *Psychological reports,* 63**,** 659-670.

JANSCH, J. & BIRKHOFER, H. 2007. Imparting Design Methods with the Strategies of Experts. *ICED07: The 16th International Conference on Engineering Design.* Paris, France.

JANSSON, D. G. & SMITH, S. M. 1991. Design fixation. *Design Studies,* 12**,** 3-11.

JONASSEN, D. H. 1997. Instructional design models for well-structured and III-structured problem-solving learning outcomes. *Educational Technology Research and Development,* 45**,** 65-94.

JONASSEN, D. H. 2000. Toward a design theory of problem solving. *Educational Technology Research and Development,* 48**,** 63-85.

KAPTELININ, V., KUUTTI, K. & BANNON, L. 1995. Activity theory: Basic concepts and applications. *Human-Computer Interaction,* 1015/1995**,** 189-201.

KARLSSON, F. & WISTRAND, K. 2006. Combining method engineering with activity theory: theoretical grounding of the method component concept. *European Journal of Information Systems,* 15**,** 82-90.

KAUFMAN, J. C. & STERNBERG, R. J. 2010. *The Cambridge Handbook of Creativity,* New York, Cambridge University Press.

KAVAKLI, M. & GERO, J. S. 2002. The structure of concurrent cognitive actions: A case study on novice and expert designers. *Design Studies,* 23**,** 25-40.

KAVAKLI, M. & GERO, J. S. 2003. Strategic knowledge differences between an expert and a novice designer. *In:* LINDEMANN, U. (ed.) *Human behaviour in design: Individuals, teams, tools.* Munich: Springer: Verlag.

KELLY, J. R. & MCGRATH, J. E. 1985. Effects of time limits and task types on task performance and interaction of four-person groups. *Journal of Personality and Social Psychology,* 49**,** 395-407.

KIM, K. H. 2006. Can we trust creativity tests? A review of the Torrance Tests of Creative Thinking (TTCT). *Creativity Research Journal,* 18**,** 3-14.

KIRTON, M. 1976. Adaptors and innovators: A description and measure. *Journal of applied psychology,* 61**,** 622-629.

KIRTON, M. J. 1978. Have adaptors and innovators equal levels of creativity. *Psychological reports,* 42**,** 695–698.

KIRTON, M. J. & FENDER, S. 1982. The Adaption-Innovation continuum, occupational type, and course selection. *Psychological Reports,* 51**,** 883-886.

KLEIN, R. 2000. Knowledge modelling in design–the MOKA framework. *Proc. Artificial Intelligence in Design'00***,** 77-102.

KLENKE, K. 2008. *Qualitative research in the study of leadership,* Amsterdam, Elsevier Science.

KNOTT, D. 2001. The place of TRIZ in a holistic design methodology. *Creativity and Innovation Management,* 10**,** 126-133.

KOBE, G. 1995. Ford's Grand Plan. *Popular Science.* FL, USA: Bonnier Corporation.

KOBERG, C. S., DETIENNE, D. R. & HEPPARD, K. A. 2003. An empirical test of environmental, organizational, and process factors affecting incremental and radical innovation. *The Journal of High Technology Management Research,* 14**,** 21-45.

KOLARIK, W. J. 1995. *Creating quality: concepts, systems, strategies, and tools,* London, McGraw-Hill.

KRIPPENDORFF, K. 1981. *Content analysis: An introduction to its methodology,* Thousand Oaks, CA, Sage.

KRUGER, C. & CROSS, N. 2006. Solution driven versus problem driven design: strategies and outcomes. *Design Studies,* 27**,** 527-548.

KRYSSANOV, V. V., TAMAKI, H. & KITAMURA, S. 2001. Understanding design fundamentals: how synthesis and analysis drive creativity, resulting in emergence. *Artificial Intelligence in Engineering,* 15**,** 329-342.

LAWSON, B. 1994. *Design in Mind,* Oxford, UK, Butterworth-Heinemann.

LAWSON, B. 2006. *How designers think: the design process demystified*, Architectural press.

LEPINE, J. A. 2003. Team Adaptation and Postchange Performance: Effects of Team Composition in Terms of Members' Cognitive Ability and Personality. *Journal of Applied Psychology,* 88**,** 27-39.

LEPINE, J. A., HOLLENBECK, J. R., ILGEN, D. R. & HEDLUND, J. 1997. Effects of Individual Differences on the Performance of Hierarchical Decision-Making Teams: Much More Than g. *Journal of Applied Psychology,* 82**,** 803-811.

LIIKKANEN, L. A. & PERTTULA, M. 2009. Exploring problem decomposition in conceptual design among novice designers. *Design Studies,* 30**,** 38-59.

LINSEY, J., TSENG, I., FU, K., CAGAN, J., WOOD, K. & SCHUNN, C. 2010. A study of design fixation, its mitigation and perception in engineering design faculty. *Journal of Mechanical Design,* 132**,** 041003.

LISSITZ, R. W. & WILLHOFT, J. L. 1985. A Methodological Study of the Torrance Tests of Creativity. *Journal of Educational Measurement,* 22**,** 1-11.

LIU, Y. C., CHAKRABARTI, A. & BLIGH, T. 2003. Towards an 'ideal' approach for concept generation. *Design Studies,* 24**,** 341-355.

LLOYD, P. & SCOTT, P. 1994. Discovering the design problem. *Design Studies,* 15**,** 125-140.

LOPEZ-MESA, B. & VIDAL, R. 2006. Novelty Metrics in Engineering Design Experiments. *Design 2006: The 9th International Design Conference.* Dubrovnik, Croatia.

LUBART, T. I. 1999. Creativity across cultures. *In:* STERNBERG, R. J. (ed.) *Handbook of Creativity.* New York: Cambridge University Press.

LUBART, T. I. 2001. Models of the Creative Process: Past, Present and Future. *Creativity Research Journal,* 13**,** 295-308.

LUBART, T. I. & GETZ, I. 1997. Emotion, metaphor, and the creative process. *Creativity Research Journal,* 10**,** 285-301.

MACEDO, L. & CARDOSO, A. 2002. Assessing creativity: the importance of unexpected novelty. *Second Workshop on Creative Systems: Approaches to Creativity in Artificial Intelligence and Cognitive Science.* Lyon, France.

MAHER, M. & DE SILVA GARZA, A. 2006. Co-evolutionary Design of Structural Layouts: A Potentially Creative Solution? Sydney, Australia: University of Sydney.

MAHER, M. & POON, J. 1995. Formalising design exploration as co-evolution: A combined gene approach. *In:* GERO, J. S. & SUDWEEKS, F. (eds.) *Advances in Formal Design Methods for CAD.* Chapman and Hall.

MAHER, M. L. 2000. A model of co-evolutionary design. *Engineering with computers,* 16**,** 195-208.

MARR, A. 2013. *A History of the World,* London, UK, Pan.

MATTHEWS, P., BLESSING, L. & WALLACE, K. 2002. The introduction of a design heuristics extraction method. *Advanced Engineering Informatics,* 16**,** 3-19.

MATTHIESEN, S. 2011. Seven years of product development in industry - experiences and requirements for supporting design with 'Thinking Tools'. *In:* CULLEY, S. J., HICKS, B. J., MCALOONE, T. C., HOWARD, T. J. & DONG, A. (eds.) *ICED11: 18th International Conference on Engineering Design.* Copenhagen, Denmark.

MCALPINE, H., HICKS, B. J. & CULLEY, S. J. 2009. Comparing the information content of formal and informal design documents: lessons for more complete design records. *ICED09: International conference on engineering design.* Stanford, CA, USA.

MCALPINE, H., HICKS, B. J., HUET, G. & CULLEY, S. J. 2006. An investigation into the use and content of the engineer's logbook. *Design Studies,* 27**,** 481-504.

MCALPINE, H., HICKS, B. J. & TIRYAKIOGLU, C. 2011. The digital divide: Investigating the personal informaiton management practices of engineers. *ICED11: 18th International Conference on Engineering Design.* Copenhagen, Denmark.

MCCOY, J. M. & EVANS, G. W. 2002. The Potential Role of the Physical Environment in Fostering Creativity. *Creativity Research Journal,* 14**,** 409-426.

MCGINNIS, B. D. & ULLMAN, D. G. 1990. The Evolution of Commitments in the Design of a Component. *Journal of Mechanical Design,* 114**,** 1-7.

MEDNICK, S. A. 1962. The associative basis of the creative process. *Psychological Review,* 69**,** 220-232.

MILNE, M. J. & ADLER, R. W. 1999. Exploring the reliability of social and environmental disclosures content analysis. *Accounting, Auditing & Accountability Journal,* 12**,** 237-256.

MOREAU, C. P. & DAHL, D. W. 2005. Designing the solution: The impact of constraints on consumers' creativity. *Journal of Consumer Research,* 32**,** 13-22.
MOTTE, D., ANDERSSON, P. & BJARNEMO, R. 2004a. A Descriptive Model of the Designer's Problem-Solving Activity During the Later Phases of the Mechanical Engineering Design Process. *CDEN Design Conference.* Montreal, Canada.
MOTTE, D., ANDERSSON, P. & BJARNEMO, R. 2004b. Study of the Designer's Cognitive Processes during the Later Phases of the Mechanical Engineering Design Process. *DESIGN 2004: The 8th International Design Conference.* Dubrovnik, Croatia.
MOTTE, D. & BJÄRNEMO, R. 2004. The cognitive aspects of the engineering design activity–A literature survey. *TMCE 2004: Tools and Methods for Concurrent Engineering.* Lausanne, Switzerland.
NGUYEN, L. & SHANKS, G. 2009. A framework for understanding creativity in requirements engineering. *Information and software technology,* 51**,** 655-662.
NIKU, A. B. 2009. *Creative design of products and systems,* New York, Wiley.
O'DONNELL, F. J. & DUFFY, A. H. B. 2002. Modelling design development performance. *International Journal of Operations & Production Management,* 22**,** 1198-1221.
OED 1989. *Oxford English Dictionary,* Oxford, Oxford University Press.
ONARHEIM, B. & WILTSCHNIG, S. 2010. Opening and Constraining: Constraints and Their Role in Creative Processes. *DESIRE'10: Creativity and Innovation in Design.* Aarhus, Denmark.
ONS 2013. 18.22 Total Engineering. *Annual Abstract of Statistics - Quarter 3, 2011.* London: Office for National Statistics.
OSBORN, A. F. 1953. *Applied imagination*, Scribner.
PAHL, G. & BEITZ, W. 1984. *Engineering Design: A Systematic Approach,* London, Springer.
PIROLA-MERLO, A. & MANN, L. 2004. The relationship between individual creativity and team creativity: Aggregating across people and time. *Journal of Organizational Behavior,* 25**,** 235-257.
PLUCKER, J. A. & BEGHETTO, R. A. 2004. Why creativity is domain general, why it looks domain specific, and why the distinction doesn't matter. *In:* STERNBERG, R. J. (ed.) *Creativity: from potential to realisation.* Washington D.C.: American Psychological Association.
POON, J. & MAHER, M. L. 1997. Co-evolution and emergence in design. *Artificial Intelligence in Engineering,* 11**,** 319-327.
POTTER, W. J. & LEVINE DONNERSTEIN, D. 1999. Rethinking validity and reliability in content analysis. *Journal of Applied Communication Research,* 27**,** 258-284.
PRABHU, V., SUTTON, C. & SAUSER, W. 2008. Creativity and Certain Personality Traits: Understanding the Mediating Effect of Intrinsic Motivation. *Creativity Research Journal,* 20**,** 53-66.
PUGH, S. 1990. *Total Design: integrated methods for successful product engineering,* Harlow, Prentice Hall.
PURCELL, A. T. & GERO, J. S. 1996. Design and other types of fixation. *Design Studies,* 17**,** 363-383.
RADCLIFFE, D. F. & LEE, T. Y. 1989. Design methods used by undergraduate engineering students. *Design Studies,* 10**,** 199-207.
REDMILES, D. 2002. Introduction to the special issue on activity theory and the practice of design. *Computer Supported Cooperative Work (CSCW),* 11**,** 1-11.
RENZULLI, J. S. 1986. The Three Ring Conception of Giftedness: A Developmental Model for Promoting Creative Productivity. *In:* STERNBERG, R. J. (ed.) *Conceptions of Giftedness.* New York: Cambridge University Press.
RHODES, M. 1961. An Analysis of Creativity. *The Phi Delta Kappan,* 42**,** 305-310.
ROBSON, C. 2002. *Real world research: A resource for social scientists and practitioner-researchers,* Oxford, Blackwell.
ROOZENBURG, N. F. M. & EEKELS, J. 1995. *Product Design: Fundamentals and Methods,* New York, John Wiley and Sons Ltd.
RUNCO, M. A. 2004. Everyone has creative potential. *In:* STERNBERG, R. J. (ed.) *Creativity: from potential to realization.* Washington D.C.: American Psychological Association.
RUNCO, M. A. & CHARLES, R. E. 1993. Judgments of originality and appropriateness as predictors of creativity. *Personality and Individual Differences,* 15**,** 537-546.
RUNCO, M. A. & SAKAMOTO, S. O. 1999. Experimental studies of creativity. *In:* STERNBERG, R. J. (ed.) *Handbook of Creativity.* New York: Cambridge University Press.

RYAN, R. M. & DECI, E. L. 2000. Intrinsic and Extrinsic Motivations: Classic Definitions and New Directions. *Contemporary educational psychology,* 25**,** 54-67.
SAATY, T. L. 1990. How to make a decision: the analytic hierarchy process. *European journal of operational research,* 48**,** 9-26.
SAMUEL, P. & JABLOKOW, K. 2011. Toward an adaption-innovation strategy for engineering design. *ICED'11: International conference on engineering design.* Copenhagen, Denmark.
SARKAR, P. & CHAKRABARTI, A. 2011. Assessing design creativity. *Design Studies,* 32**,** 348-383.
SCARAVETTI, D., SEBASTIAN, P., PAILHES, J. & NADEAU, J. 2006. Exploring design spaces in the search for embodiment design solutions and decision support. *IMACS Multiconference on Computational Engineering in Systems Applications (CESA).* Beijing, China: IEEE.
SCHON, D. A. 1983. *The reflective designer: How professionals think in action,* New York, Basic Books.
SEITAMAA-HAKKARAINEN, P. & HAKKARAINEN, K. 2001. Composition and construction in experts' and novices' weaving design. *Design Studies,* 22**,** 47-66.
SHAH, J. J., SMITH, S. M. & VARGAS-HERNANDEZ, N. 2003. Metrics for measuring ideation effectiveness. *Design Studies,* 24**,** 111-134.
SHALLEY, C. E. 1991. Effects of productivity goals, creativity goals, and personal discretion on individual creativity. *Journal of applied psychology,* 76**,** 179.
SHALLEY, C. E. & GILSON, L. L. 2004. What leaders need to know: A review of social and contextual factors that can foster or hinder creativity. *The Leadership Quarterly,* 15**,** 33-53.
SHNEIDERMAN, B. 2000. Creating creativity: user interfaces for supporting innovation. *ACM Transactions on Computer-Human Interaction (TOCHI),* 7**,** 114-138.
SIMON, H. A. 1973. The structure of ill structured problems. *Artificial Intelligence,* 4**,** 181-201.
SIMON, H. A. & CHASE, W. G. 1973. Skill in Chess: Experiments with chess-playing tasks and computer simulation of skilled performance throw light on some human perceptual and memory processes. *American Scientist,* 61**,** 394-403.
SIMONTON, D. K. 1984. *Genius, creativity and leadership*, Harvard University Press.
SIMONTON, D. K. 1999. *Origins of genius: Darwinian perspectives on creativity*, Oxford University Press.
SMITH, R. P. & TJANDRA, P. 1998. Experimental observation of iteration in engineering design. *Research in engineering design,* 10**,** 107-117.
SMULDERS, F. E., DORST, K. & REYMEN, I. M. 2009. Modelling co-evolution in design practice. *In:* NORELL BERGENDAHL, M., GRIMHEDEN, M., LEIFER, L., SKOGSTAD, P. & LINDEMANN, U. (eds.) *ICED11: 17th International Conference on Engineering Design.* Stanford, CA.
SNIDER, C. M., CASH, P. J., DEKONINCK, E. A. & CULLEY, S. J. 2012a. Variation in creative behaviour during the later stages of the design process. *ICDC2012: The 2nd International Conference on Design Creativity.* Glasgow, Scotland.
SNIDER, C. M., CULLEY, S. J. & DEKONINCK, E. A. 2013a. Analysing creative behaviour in the later stage design process. *Design Studies,* 34**,** 543-574.
SNIDER, C. M., CULLEY, S. J. & DEKONINCK, E. A. 2013b. Determining relative quality for the study of creative design output. *ICoRD'13: International Conference on Research into Design.* Chennai, India.
SNIDER, C. M., DEKONINCK, E. A. & CULLEY, S. J. 2012b. Improving confidence in smaller data sets through methodology: The development of a coding scheme. *DESIGN 2012: The 12th International Design Conference.* Dubrovnik, Croatia.
SNIDER, C. M., DEKONINCK, E. A. & CULLEY, S. J. 2014. The appearance of creative behavior in later stage design processes. *International Journal of Design Creativity and Innovation,* 2**,** 1-19.
SOBEK, D. K. 2002. Representation in design: data from engineering journals. *ASEE/IEEE: 32nd Frontiers in Education Conference.* Boston, MA.
SOSA, R. & GERO, J. S. 2003. Design and change: a model of situated creativity. *IJCAI Creativity Workshop.* Acapulco, Mexico.
STEMPFLE, J. & BADKE-SCHAUB, P. 2002. Thinking in design teams-an analysis of team communication. *Design studies,* 23**,** 473-496.
STERNBERG, R. J. 2011. *Explorations in Giftedness,* New York, Cambridge University Press.
STERNBERG, R. J. & LUBART, T. I. 1996. Investing in creativity. *American psychologist,* 51**,** 677.
STERNBERG, R. J. & LUBART, T. I. 1999. The concept of creativity: prospects and paradigms. *In:* STERNBERG, R. J. (ed.) *Handbook of creativity.* New York: Cambridge University Press.

STERNBERG, R. J. & O'HARA, L. A. 1999. Creativity and intelligence. *In:* STERNBERG, R. J. (ed.) *Handbook of Creativity.* New York: Cambridge University Press.

STERNBERG, R. J. E. 1999. *The Handbook of Creativity,* New York, Cambridge University Press.

STEWART, G. L. 2006. A Meta-Analytic Review of Relationships Between Team Design Features and Team Performance. *Journal of Management,* 32**,** 29-55.

STOKES, M. E. 2001. *Managing Engineering Knowledge,* London, Professional Engineering Publishing Limited.

STOKES, P. D. 2006. *Creativity from constraints: the psychology of breakthrough*, Springer Pub. Co.

STOKES, P. D. 2007. Using constraints to generate and sustain novelty. *Psychology of Aesthetics, Creativity, and the Arts,* 1**,** 107.

STOKES, P. D. 2009. Using Constraints to Create Novelty: A Case Study. *Psychology of Aesthetics, Creativity, and the Arts,* 3**,** 174-180.

SUH, N. P. 1990. *The principles of design,* Oxford, UK, Oxford University Press.

SUMMERS, J. D. & SHAH, J. J. 2010. Mechanical Engineering Design Complexity Metrics: Size, Coupling, and Solvability. *Journal of Mechanical Design,* 132**,** 021004-021004.

SUWA, M., GERO, J. & PURCELL, T. 2000. Unexpected discoveries and S-invention of design requirements: important vehicles for a design process. *Design Studies,* 21**,** 539-567.

TERMAN, L. M. & ODEN, M. H. 1959. *Volume 5: Genetic studies of genius: The gifted group at mid-life,* Stanford, Stanford University Press.

THAMHAIN, H. J. & WILEMON, D. L. 1987. Building high performing engineering project teams. *Engineering Management, IEEE Transactions on,* EM-34**,** 130-137.

THOMAS, J. C. & CARROLL, J. M. 1979. The psychological study of design. *Design Studies,* 1**,** 5-11.

THOMPSON, G. & LORDAN, M. 1999. A review of creativity principles applied to engineering design. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering,* 213**,** 17-31.

TOMIYAMA, T., GU, P., JIN, Y., LUTTERS, D., KIND, C. & KIMURA, F. 2009. Design methodologies: Industrial and educational applications. *CIRP Annals - Manufacturing Technology,* 58**,** 543-565.

TORRANCE, E. P. 1980. Creativity and style of learning and thinking characteristics of adaptors and innovators. *Creative Child & Adult Quarterly*.

TORRANCE, E. P. 1998. *Torrance Tests of Creative Thinking: Norms-technical Manual: Figural (streamlined) Forms A & B,* Bensenville, IL, Scholastic Testing Service Inc.

TORRANCE, E. P. 2008. *Torrance Test of Creative Thinking: Norms-Technical Manual Figural (Streamlined) Forms A & B,* Bensenville, IL, Scolastic Testing Service Inc.

TREFFINGER, D. J. 1985. Review of the Torrance Tests of Creative Thinking. *In:* MITCHELL, J. V. (ed.) *The ninth mental measurements yearbook.* University of Nebraska, Buros Institute of Mental Measurements: Lincoln.

ULLMAN, D., DIETTERICH, T. & STAUFFER, L. 1988a. A model of the mechanical design process based on empirical data. *AI EDAM,* 2**,** 33-52.

ULLMAN, D. G. 1997. *The mechanical design process,* London, McGraw-Hill.

ULLMAN, D. G., DIETTERICH, T. G. & STAUFFER, L. A. 1988b. A model of the mechanical design process based on empirical data. *AI EDAM,* 2**,** 33-52.

ULRICH, K. 1995. The role of product architecture in the manufacturing firm. *Research Policy,* 24**,** 419-440.

ULRICH, K. & EPPINGER, S. D. 2012. *Product design and development,* New York, McGraw-Hill.

ULRICH, K. & PEARSON, S. 1993. Does product design really determine 80% of manufacturing cost? Cambridge, MA: Sloan school of management, MIT, MA.

VAIDYA, O. S. & KUMAR, S. 2006. Analytic hierarchy process: An overview of applications. *European journal of operational research,* 169**,** 1-29.

VAN MERRIËNBOER, J. J. & SWELLER, J. 2005. Cognitive load theory and complex learning: Recent developments and future directions. *Educational psychology review,* 17**,** 147-177.

VDI-RICHTLINIE 1993. *2221: Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte,* Düsseldorf, VDI-Verlag.

VISSER, W. 1990. More or less following a plan during design: opportunistic deviations in specification. *International Journal of Man-Machine Studies,* 33**,** 247-278.

VISSER, W. 1994. Organisation of design activities: opportunistic, with hierarchical episodes. *Interacting with computers,* 6**,** 239-274.

VISSER, W. 2006. *The Cognitive Artifacts of Designing,* Mahwah, New Jersey, Lawrence Erlbaum Associates.

VOSS, J. F., GREENE, T. R., POST, T. A. & PENNER, B. C. 1983. Problem-solving skill in the social sciences. *The psychology of learning and motivation,* 17**,** 165-213.

WALDMAN, D. A. 1994. The contributions of total quality management to a theory of work performance. *Academy of Management Review,* 19**,** 510-536.

WALLAS, G. 1926. *Art of thought,* London, C. A. Watts & Co. Ltd.

WARD, T. B. 1994. Structured Imagination: the Role of Category Structure in Exemplar Generation. *Cognitive Psychology,* 27**,** 1-40.

WARD, T. B., DODDS, R. A., SAUNDERS, K. N. & SIFONIS, C. M. 2000. Attribute centrality and imaginative thought. *Memory & cognition,* 28**,** 1387-1397.

WARD, T. B., PATTERSON, M. J. & SIFONIS, C. M. 2004. The role of specificity and abstraction in creative idea generation. *Creativity Research Journal,* 16**,** 1-9.

WILTSCHNIG, S., CHRISTENSEN, B. T. & BALL, L. J. 2013. Collaborative problem–solution co-evolution in creative design. *Design Studies,* In Press.

YILMAZ, S. & SEIFERT, C. M. 2011. Creativity through design heuristics: A case study of expert product design. *Design Studies,* 32**,** 384-415.

YOUMANS, R. J. 2011. The effects of physical prototyping and group work on the reduction of design fixation. *Design Studies,* 32**,** 115-138.

Appendix I

The following pages replicate the background questionnaire given to participants in studies two and four.

Please fill out this questionnaire in order to give some contextual information on your background, training and experience.

If you do not wish to answer any question for any reason please mark as such and move on. This questionnaire will not be used to reflect on you personally.

All answers will remain strictly confidential and will be used for characterisation and generalisation purposes only. All answers will be anonymised.

If your answer is not accommodated in the options provided, please include your answer in the 'other' section at the end of the question. Space is provided at the end of the questionnaire for any comments you may have.

Section 1 – Personal and Socio-economic Background

1. What is your name and gender?

	M / F

2. What is your age?

3. What is your postcode?

4. What is your current occupation?

5. What is your highest level of education, and where awarded? (Please include any equivalent vocational or other education at the relevant level).

Doctoral degree
Master's degree
Bachelor's degree
Associate degree
Some university, totalling 1 2 3 4 years (please circle as appropriate)
School A-levels
School GCSE's
Institution at which highest level of education achieved …………………………………………………

6. What is your gross individual income per year?

£0 - £9,999	
£10,000 - £19,999	
£20,000 - £29,999	
£30,000 - £39,999	
£40,000 - £49,999	
£50,000 - £59,999	
£60,000 - £69,999	
£70,000 - £79,999	
£80,000 - £89,999	
£90,000 - £99,999	
£100,000 and above	

7. What is your level of property ownership?

Rent
Own single house with mortgage
Own single house without mortgage
Own multiple properties (please state number and type)
Other (please explain)

Section 2 – Higher Educational Background

8. What A levels (or equivalent) have you achieved?

Subject	Grade

9. What Degree(s) or equivalent have you achieved?

Level	Institution	Description

10. Any other education or qualifications of note?

Type	Institution	Description

Section 3 – Professional background.

Please include any experience you may have, that occurred within any single company over 6 months or longer.

11. Previous employment

Company	Duration	Job role	Responsibilities / Comments

12. University placement(s) during degree (if applicable)

Company	Duration	Job role	Responsibilities / Comments

13. What would you describe as your area of expertise?

Any comments or feedback

Appendix II

The following replicates the brief that was given to participants in study two.

Welcome to the Bath Engineering Design experiment

Understanding how engineers' work is vital to effectively communicating engineering research to industry. One means to achieve this is through the study of teams of young designers. Areas of particular and sustained interest include information seeking, creativity, design development and design review.

By taking part in this exciting study *you* will be helping to push back the boundaries of understanding in these areas. In addition to supporting much of the research carried out in this department this study gives you a chance to gain an insight into your own design practice.

All results will be anonymised during analysis and publication – All data will be stored securely and destroyed in accordance with the data protection act.

The study is in 5 parts:

1. Two short questionnaires
2. Task 1: An information seeking activity
3. Task 2: A brainstorming activity
4. Task 3: A design development activity
5. Task 4: A design review activity

Q: Why do we care about these tasks?

A: Collectively these tasks account for nearly 30% of an engineer's time and are worth millions of pounds to the UK economy. Better understanding these activities allows researchers to more effectively make changes, develop tools or simply solve engineering design problems.

Q: What do you get out of this study?

A: In addition to the financial incentive there are several other motivating factors you may be interested in. Based on the tasks in this study you will have the opportunity to gain a better understanding of your own design activity and potentially identify areas that you can develop in the future. We will also be generating a measure of your creative style and level - things often assessed during job interviews – these will be fed back to you individually.

Experimental Brief - TASK 1

This is an individual task using the computer provided and will last for fifty minutes. Please do not talk to the other participants at this stage.

You are free to use the notepad and computer provided, as well as any books or catalogues you choose in the DAC. Please search for information in order to fulfil the following brief:

"You are to design a universal camera mount for use on an aerial vehicle. The aerial vehicle is to be used by an amateur photographer, primarily to take still photos. Using any means available to you search for and note down information that may help."

You will be told when to begin by the researcher who will also let you know when there is 5 minutes left.

If you have any further questions please ask now.

Experimental Brief - TASK 2

This is a group task using the meeting area provided and will last for fifty minutes. Please feel free to discuss and make notes etc. as you wish. You are free to use the notepad, whiteboard and notepaper provided.

During this task we would like you to brainstorm ideas to fulfil the following brief. The aim of this task is to generate as many viable ideas as possible within the time available. Please record these ideas on the whiteboard as they occur but feel free to make additional notes as necessary.

"Using the specification provided, develop a variety of concepts capable of mounting any camera, while slung under a helium balloon. The mount must be capable of orientating the camera to any point in a hemi-spherical plane underneath the balloon, and must be operated remotely."

Please see the attached sheets for more information.

You will be told when to begin by the researcher who will also let you know when there is 5 minutes left.

If you have any further questions please ask now.

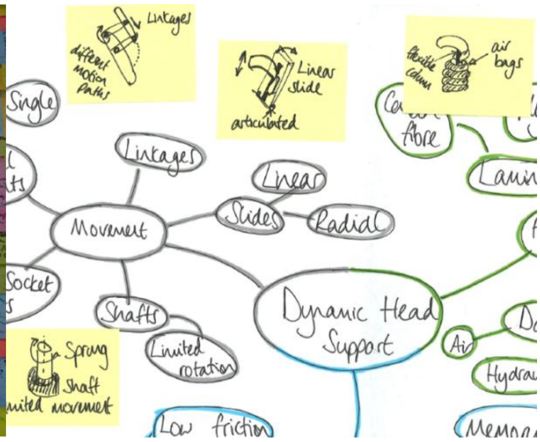
Brainstorming

Produce as many ideas as possible.

Consider all information that you have gathered in stage 1.

Consider as many technologies, products, theories and systems as possible.

Be supportive of all ideas proposed. Instead of finding faults, suggest ways that they could be improved.

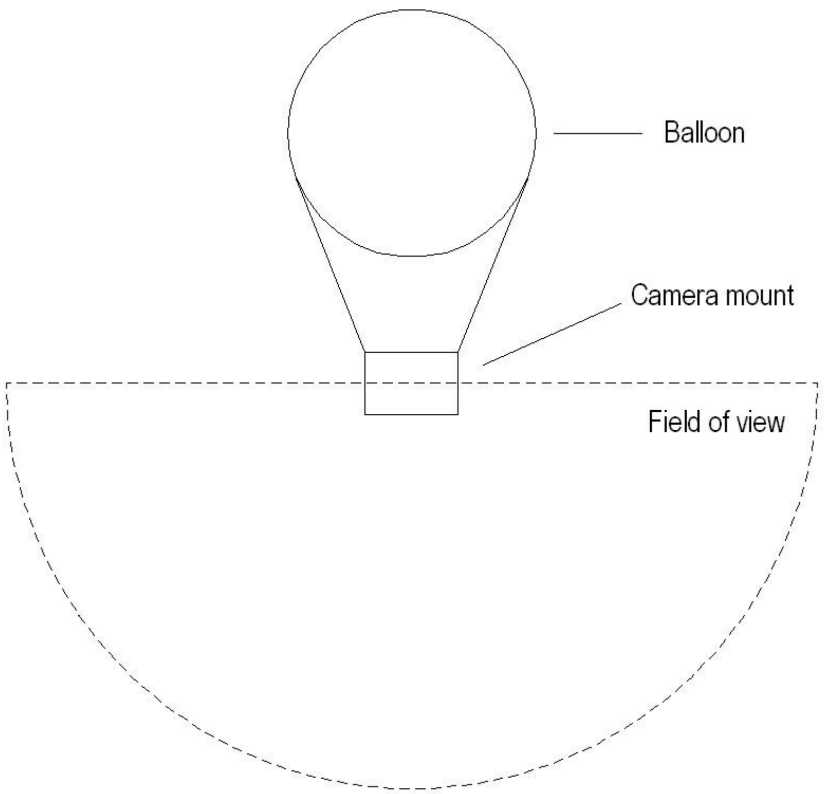


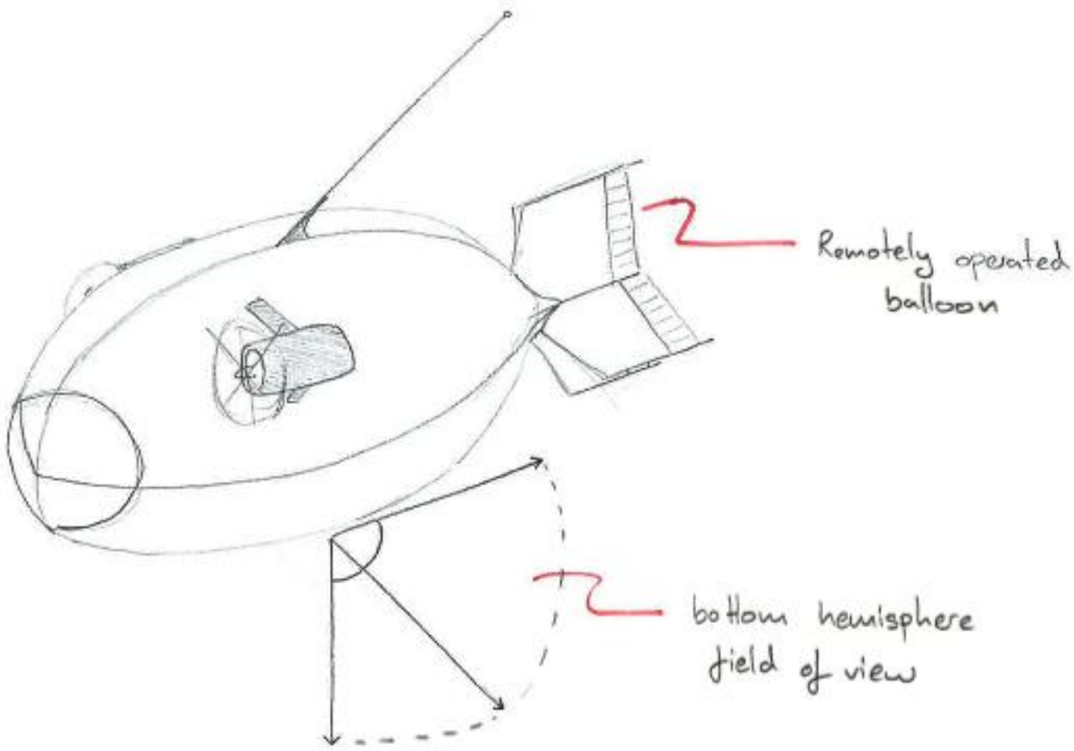
Specification

Total mass of camera and mount	*6kg*
Must take a range of cameras within weight limits	
Cost (cost price) of the mount	*£75*
Operational life (per charge)	*1.5 hours*
Speed of operation – 360^o pan	*max 30s min 10s*
Type of control	*via laptop*
Range of controller	*100m*
Range of rotation	*360^o by 180^o*
Volumetric size	*200x200x150mm*
Balloon connection	*flexible*
Balloon size	*Spherical -*

The design for the balloon has already been finalised, and is tolerant of any connection or interface with the camera mount.

Although you should try to minimise motion in the mount where possible, you do not need to consider vibration.


Balloon
Camera mount
Field of view


Remotely operated balloon
bottom hemisphere field of view

Experimental Brief - TASK 3

This is an individual task using the computer provided and will last for one and half hours. Please do not talk to the other participants at this stage.

During this task we would like you to develop one (1) of the concepts discussed during your brainstorming session based on the following brief. You are free to use the computer and notepad provided as well as any books you wish from the DAC. Develop your concept to as high a level of detail as possible. Please record each action in your logbook as you proceed.

"Develop an appropriate, feasible, dimensioned, detailed solution."

Further details

Available machines for manufacture: lathe, end mill, injection moulding, laser cutter

Assembly: By hand

Your work from this stage will be given to a skilled technician, who will build a fully operational prototype. It must therefore include:

- *General dimensions*
- *All critical dimensions*
- *Materials to be used*
- *A description of the mode of operation of all systems*
- *A description of the method of assembly*
- *A description of how the design completes its function*
- *Preferred methods of manufacture*

Although unfamiliar with the project, the technician will attempt to fill in any information that they need, should you not provide it.

Complete as much work as you can, within the time allotted.

You will be told when to begin by the researcher who will also let you know when there is 5 minutes left.

If you have any further questions please ask now.

Experimental Brief - TASK 4

This is a group task using the meeting area provided and will last for fifty minutes. Please feel free to discuss and make notes etc. as you wish. You are free to use the notepad and notepaper provided (please do not use the whiteboard for this task). During this stage one member will be asked to take a team leader role and should pay particular attention to delivering the final concept as outlined below.

During this task we would like you to review your designs (as developed in the previous task). The aim of this task is to select and develop one (or a combination of ideas) into a final concept to be taken forward to production. Please see the following brief:

"With your colleagues, and using your detailed developed concepts, select and further develop a single, final concept that best fulfils the brief and specification. Please record this final concept on a single sheet of the provided A3 paper."

You will be told when to begin by the researcher who will also let you know when there is 5 minutes left.

If you have any further questions please ask now.

Experimental Debrief

The aim of this study has been to develop a detailed picture of trainee engineers design behaviours and activities when confronted with a number of different commonly encountered design situations. This data will be used to compare with data from industrial engineers who have also completed this study. Based on this comparison a qualitative and quantitative measure of similarity will be developed for the information seeking, creativity and reviewing tasks. This will then be used to support the validation of experiments conducted using trainee engineers such as you – a critical issue in engineering design research today.

If you are interested in discussing the implications of this work further please approach either of the researchers conducting the study, who will be more than happy to provide you with further information.

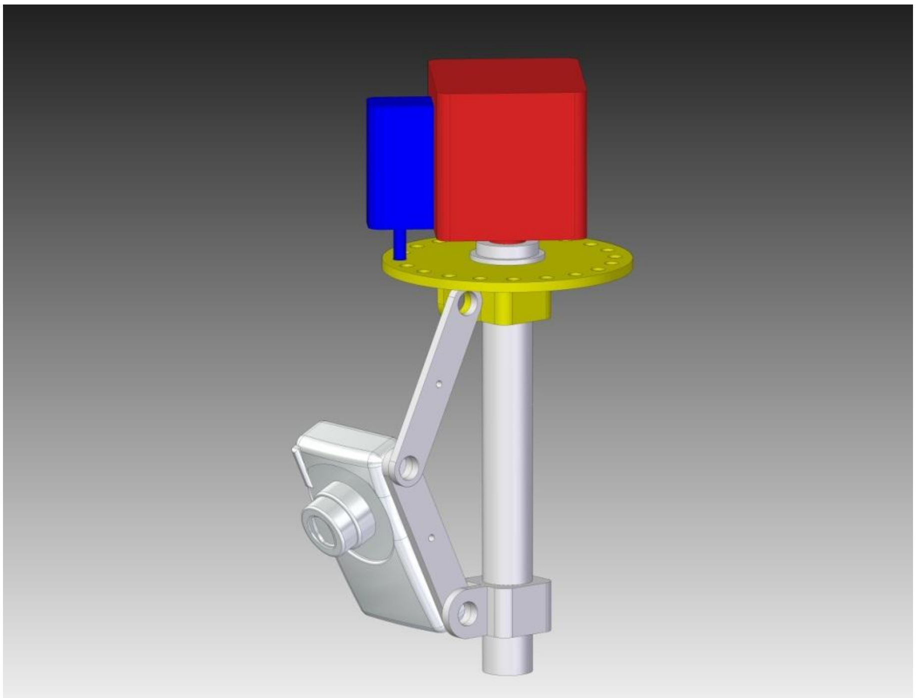
Thank you for your time – without you this research would not be possible

Thanks from Phil and Chris!

Appendix III

The following presents a sample of the survey sheets used in the quality analysis, and hence also presents a sample of the design solutions produced by designers within study two. In total, seventeen sheets were produced.

Design One



The Motor (red) drives a long Lead screw that passes clean through the Disc (yellow), and into and through a threaded Lower Mount. When powered, the Lower Mount rotates with the lead screw, causing the Disc to rotate and the camera to rotate in the horizontal plane. A Solenoid (blue) can be engaged to holes on the Disc. When engaged, the Disc cannot rotate relative to the motor, and the lower mount is driven up or down the Lead screw. This alters the vertical angle of the camera.

Please place an [X] within the box to show your rating of the design for the following:

	1 - Bad	2	3	4	5 - Good
Function completion					
Concept					
Implementation					
Manufacture and assembly					
Overall quality					
Originality					
Appropriateness to the brief					
Value					
Creativity					

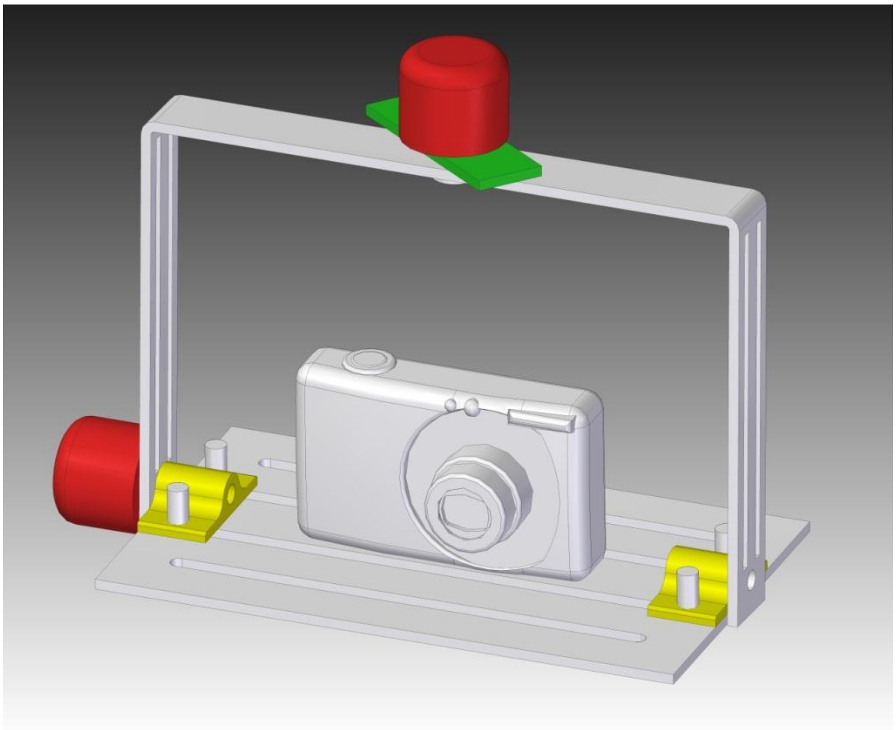
If you had to choose a particular strength of the design, what would it be?

………

If you had to choose a particular weakness of the design, what would it be?

………

Design Two



The upper Motor (red) is mounted on the upper plate (green), on which control and batteries would be mounted. The upper Motor rotates the entire frame in the horizontal plane, while the lower Motor passes through the outer frame to the Pivots (yellow), on which the camera Plate rotates in the vertical plane.

Please place an [X] within the box to show your rating of the design for the following:

	1	2	3	4	5
Function completion					
Concept					
Implementation					
Manufacture and assembly					
Overall quality					
Originality					
Appropriateness to the brief					
Value					
Creativity					

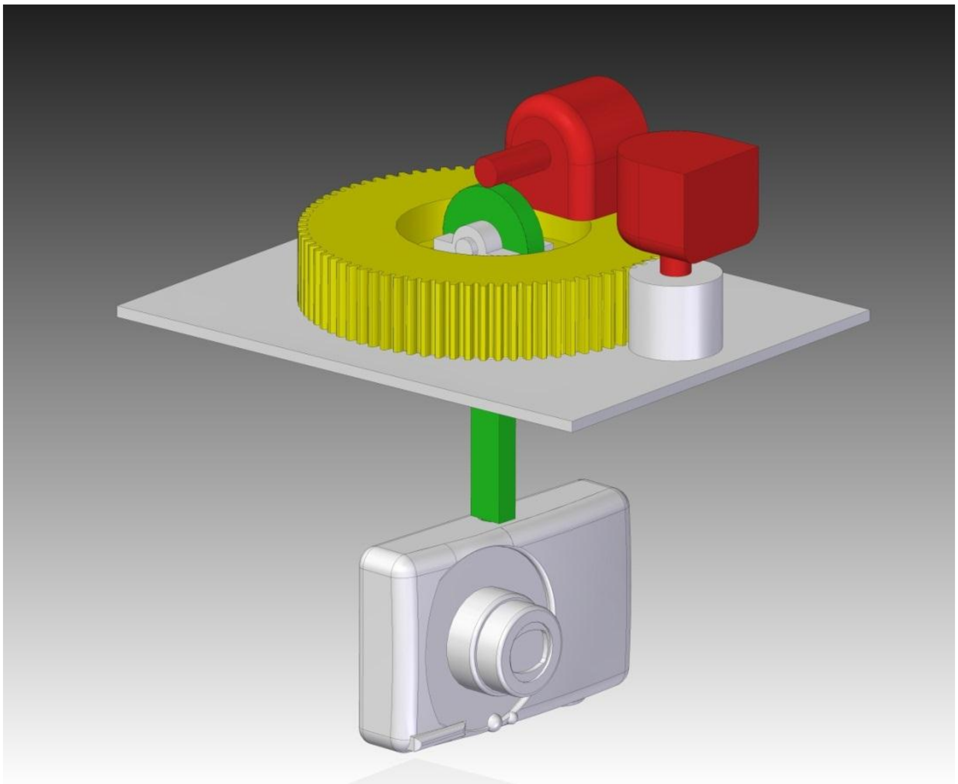
If you had to choose a particular strength of the design, what would it be?

………

If you had to choose a particular weakness of the design, what would it be?

………

Design Three



Two Motors (red) create the motion. One is mounted on the Gear (yellow), which has a central hole connected to a pivot. This pivot rotates the camera Rod (green). The second motor rotates the Gear, changing the horizontal direction in which the camera faces.

Please place an [X] within the box to show your rating of the design for the following:

	1	2	3	4	5
Function completion					
Concept					
Implementation					
Manufacture and assembly					
Overall quality					
Originality					
Appropriateness to the brief					
Value					
Creativity					

If you had to choose a particular strength of the design, what would it be?

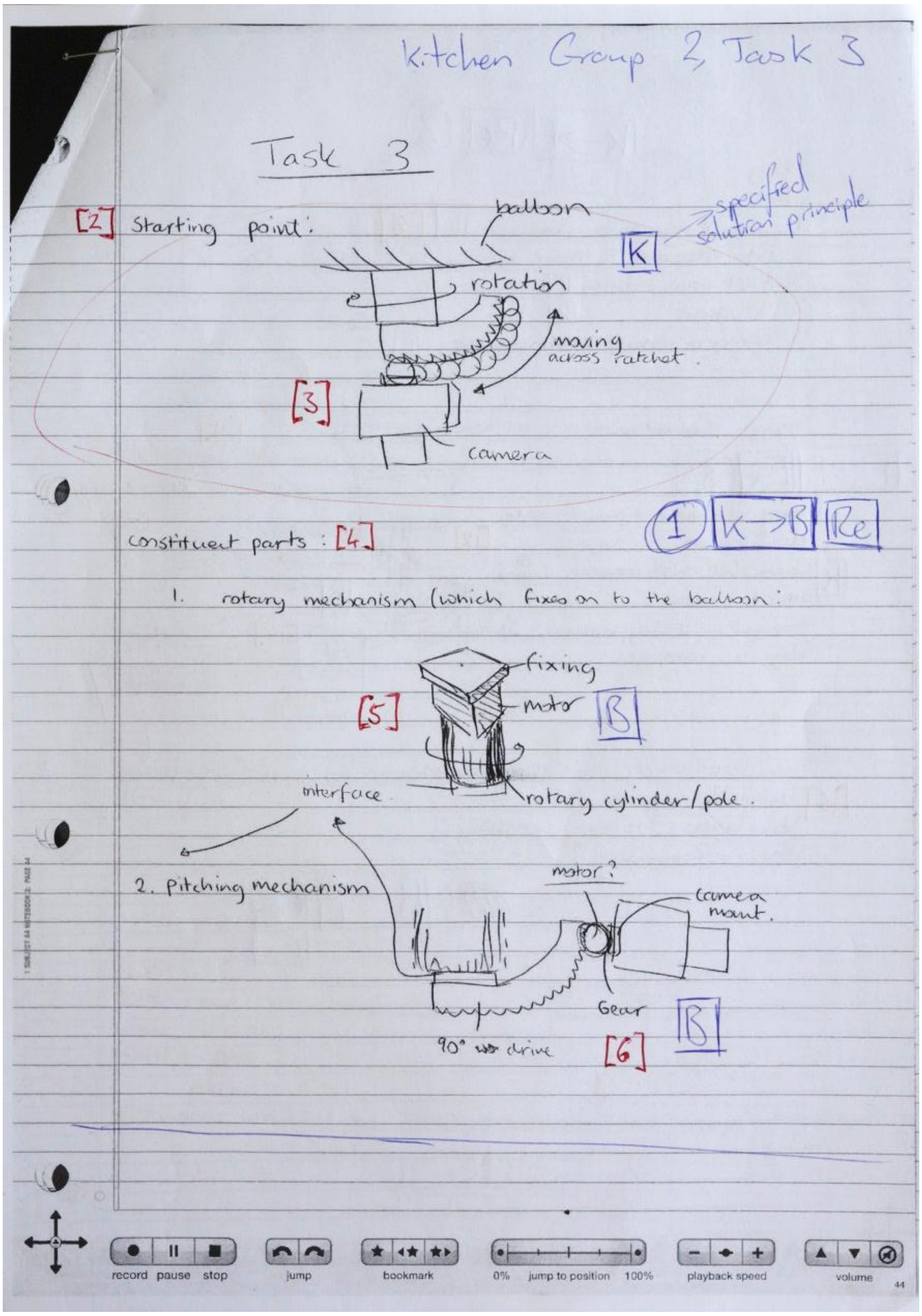
....

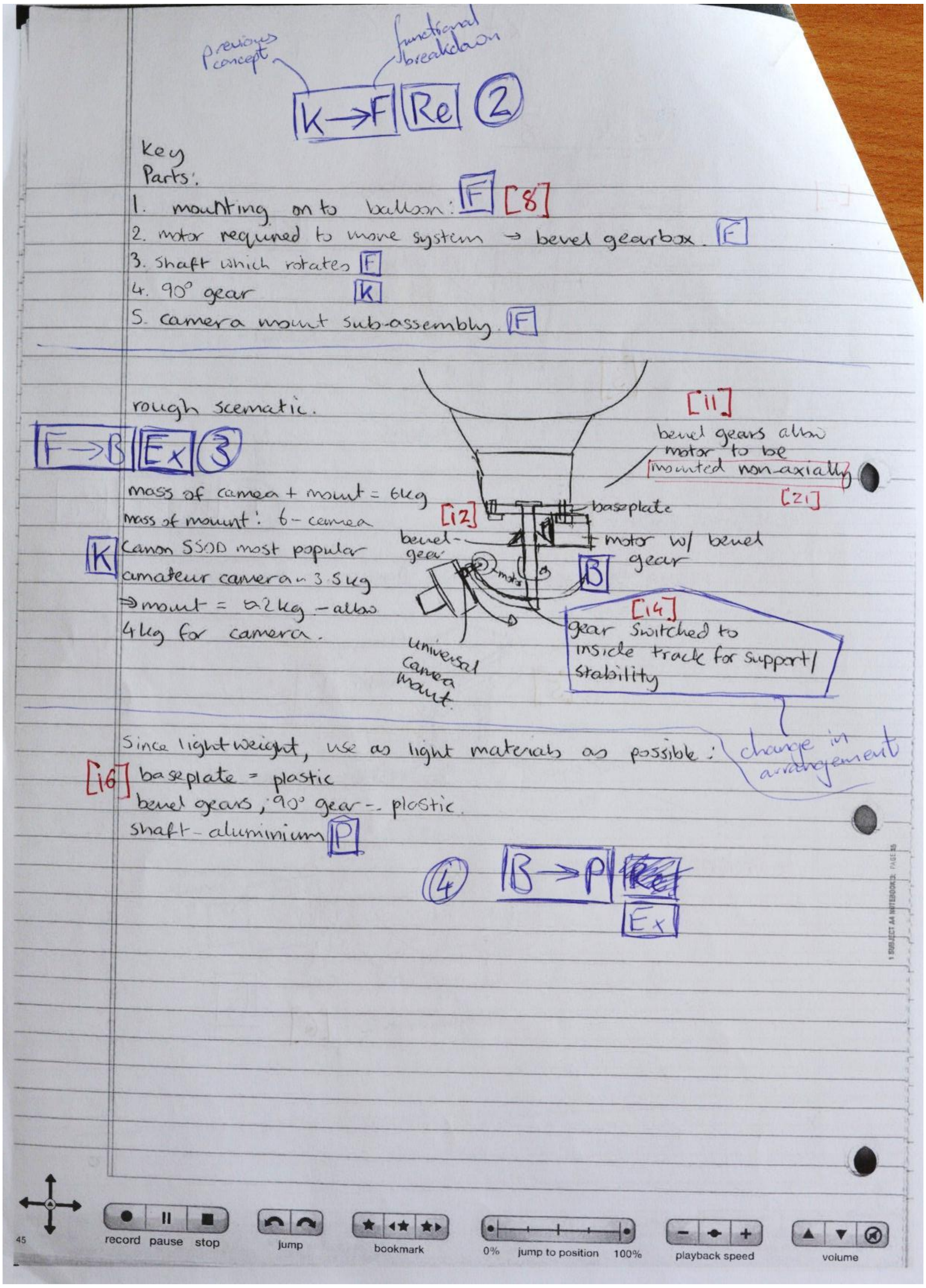
If you had to choose a particular weakness of the design, what would it be?

....

Appendix IV

The following presents a sample of the raw logbook data produced within study two, that of participant 2E. These scripts are as coded, and represent several stages of the coding process. Numbers in square brackets (red, in original copy) indicate time in minutes at which markings were made, although a more detailed breakdown was recorded digitally. Letters in squares indicate an entity. Letters linked with an arrow indicate a task transformation. Numbers in circles (blue) indicate a task number. Note that [P] entities are *structure* entities as within the thesis, due to a change in terminology through the research. Descriptions of all 19 tasks are located at the end.





previous concept

functional breakdown

K→F | Re | 2

Key
Parts:
1. mounting onto balloon: F [8]
2. motor required to move system → bevel gearbox. F
3. Shaft which rotates F
4. 90° gear K
5. camera mount sub-assembly. F

rough scematic.

F→B | Ex | 3

mass of camera + mount = 6kg
mass of mount: 6 - camera
K Canon 550D most popular amateur camera ~ 3.5kg
⇒ mount = ~2kg - allow 4kg for camera.

Since light weight, use as light materials as possible:
[16] baseplate = plastic
bevel gears, 90° gear - plastic.
shaft - aluminium P

4 | B→P | ~~Re~~ Ex

K->P Ex 5

[21]

Roughly scale Drawing of mounting assembly: K

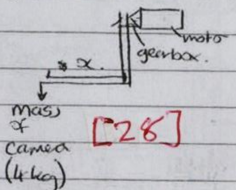
motor selection - are R/C blimps AC or DC? use batteries - DC [22]

[23]

So DC motor will not require convertor -> lightweight — considering best for design ∴ options Ex

4 x AA batteries = 1.5V. P

[26] motor load requirement ; assume must rotate whole 8kg in 30 seconds:



[28]

Calcs

B->K 6

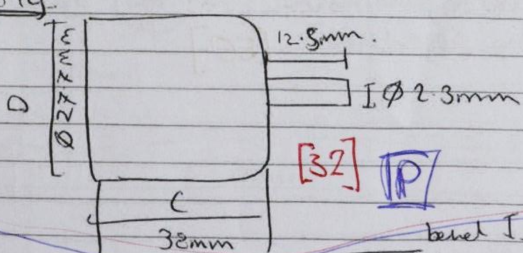
no time to calculate load requirements / inertial load on motor: so will choose most powerful + use favourable gearing; [30]

RS online

Como Drills 719RE380 6VD.C. 7.4W output 19k RPM 3.68Ncm £3.92

[31] K

Weight 69g



[32] P

K->P Re 7

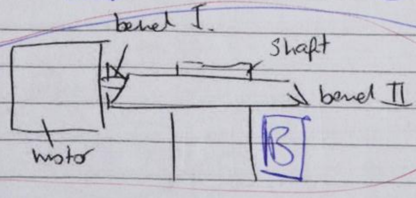
[35]

Bevel gear: very high ratio

output RPM = 19k

desired = 6 Calcs

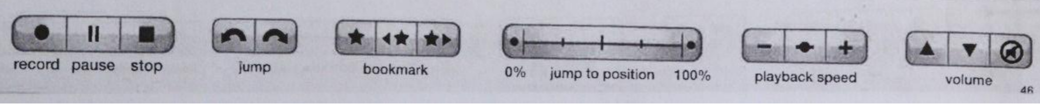
19k/6 = 3000 : 1.

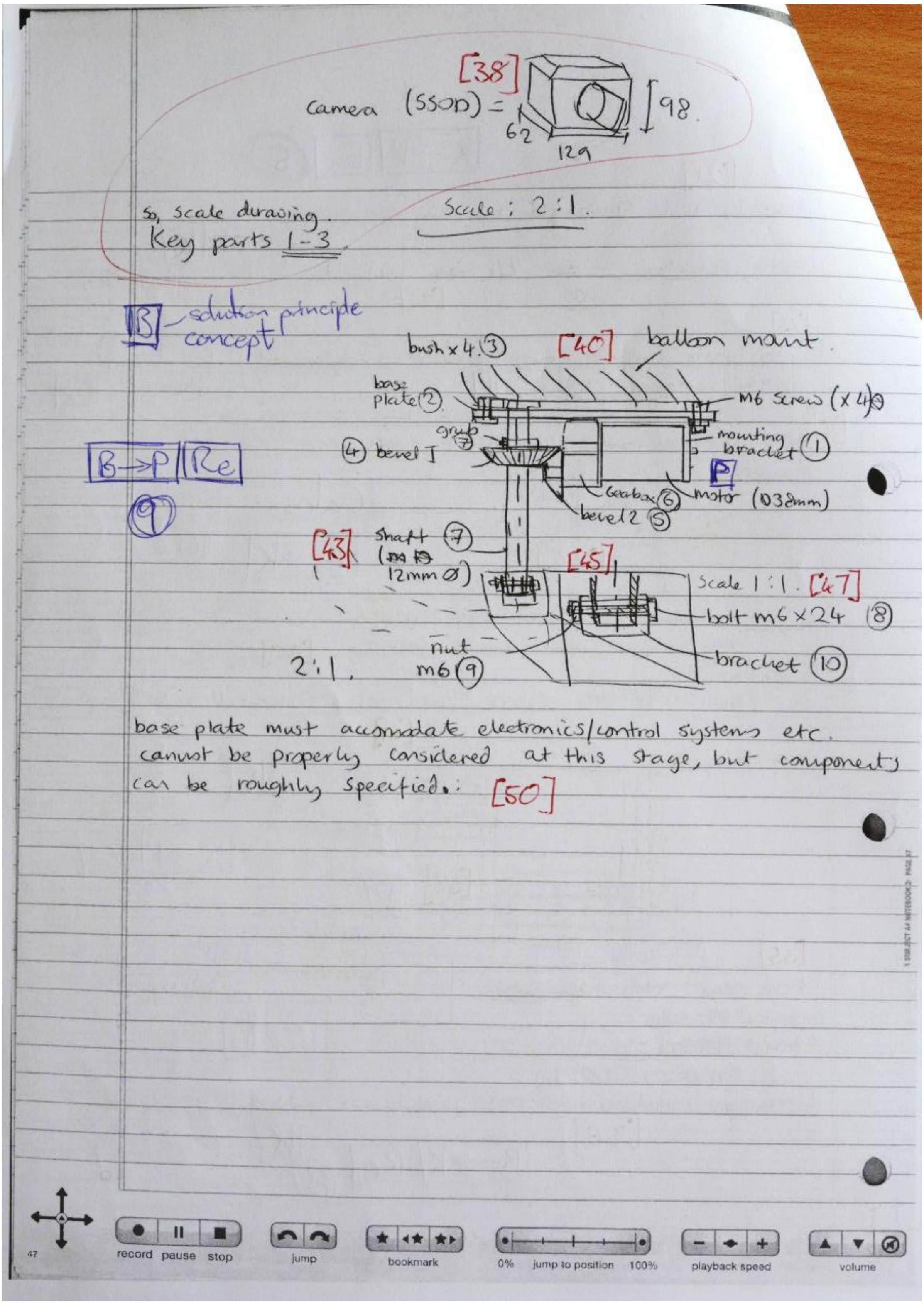


B

If necessary, conrad sell a 3000:1 gearbox - MFA Part no 22237689 £26.98

[36] B->K Re 8 K



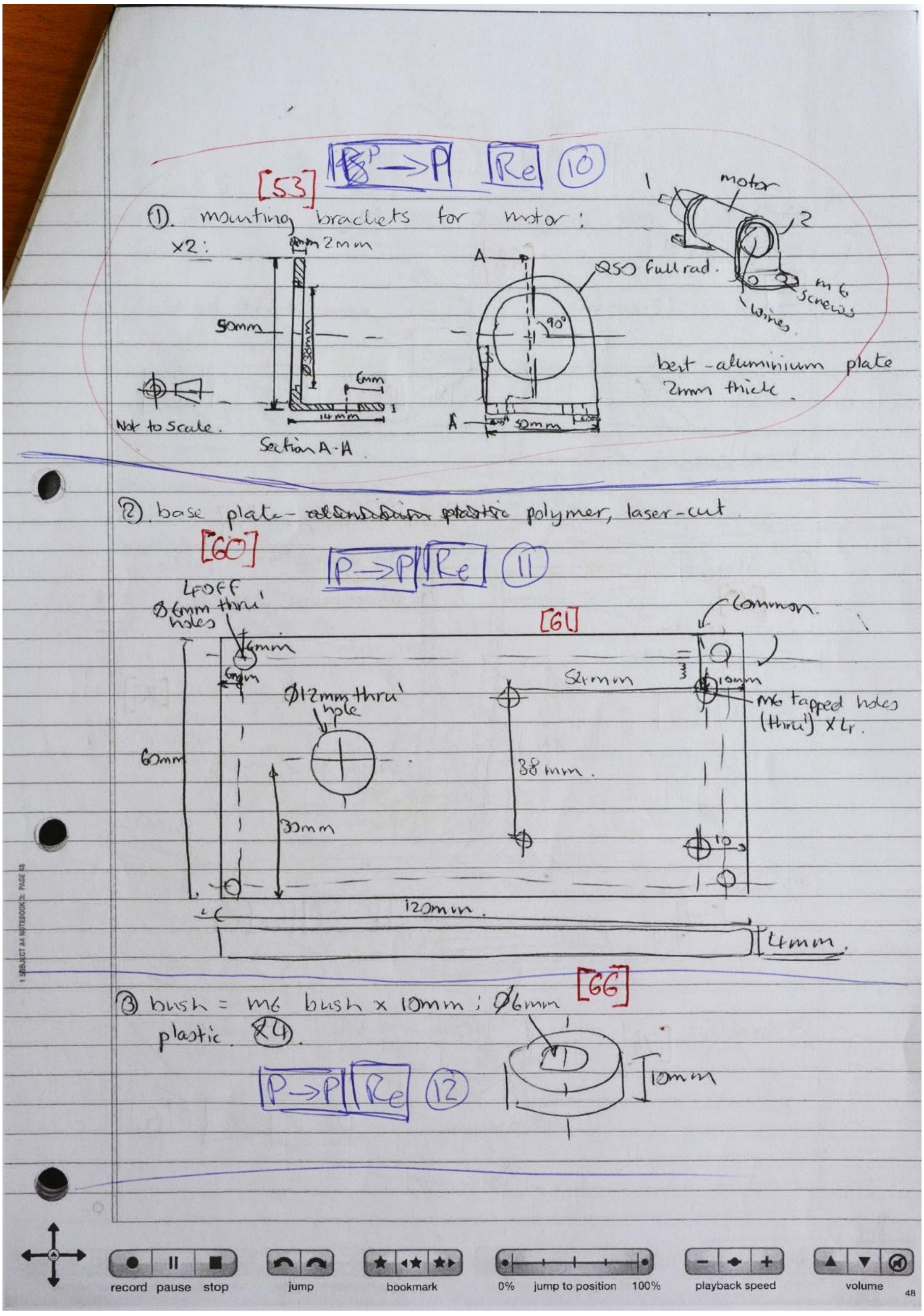

[38]
camera (550D) = 62 129 98.

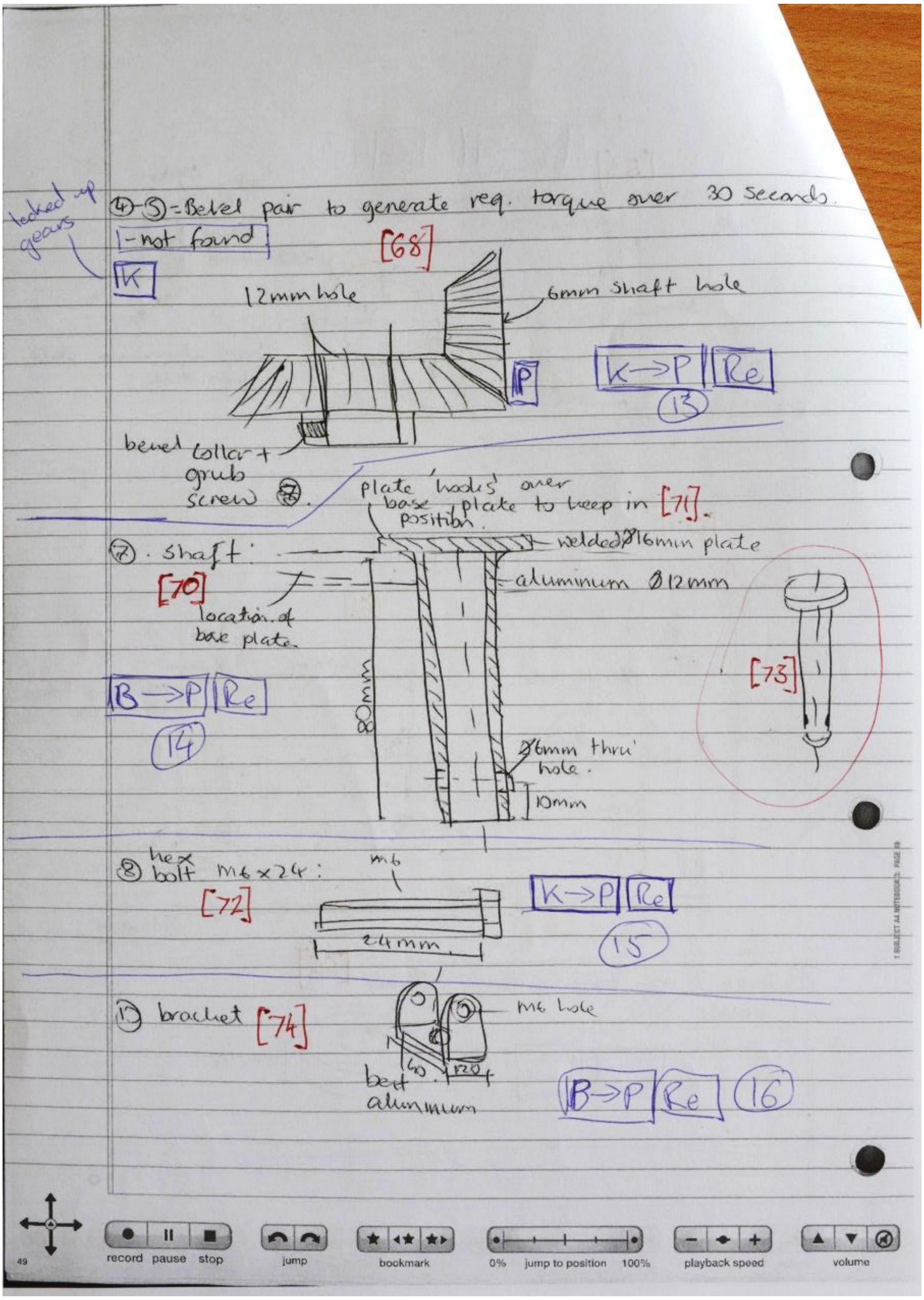
so, scale drawing. Scale : 2:1.
Key parts 1-3.

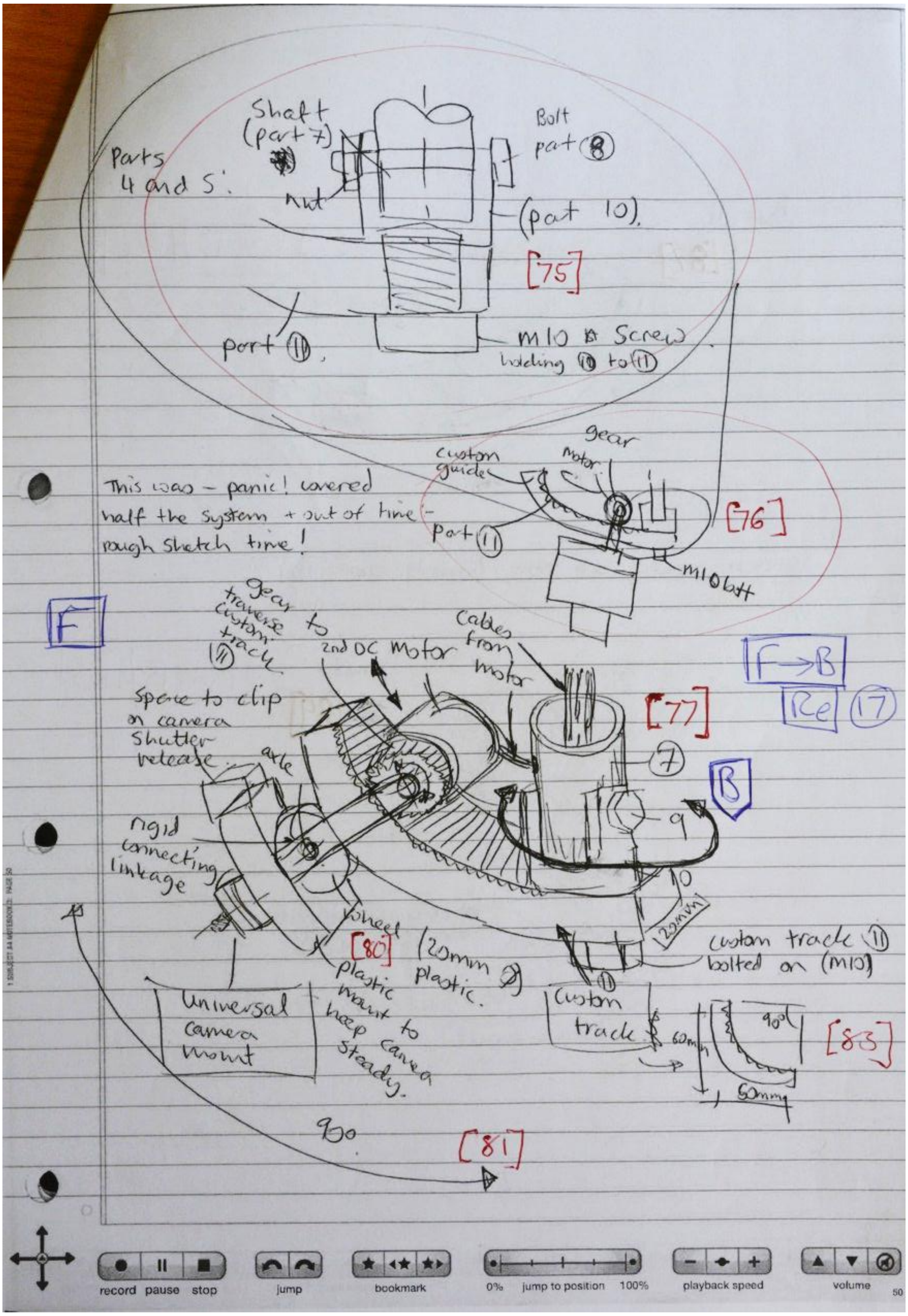
B - solution principle concept

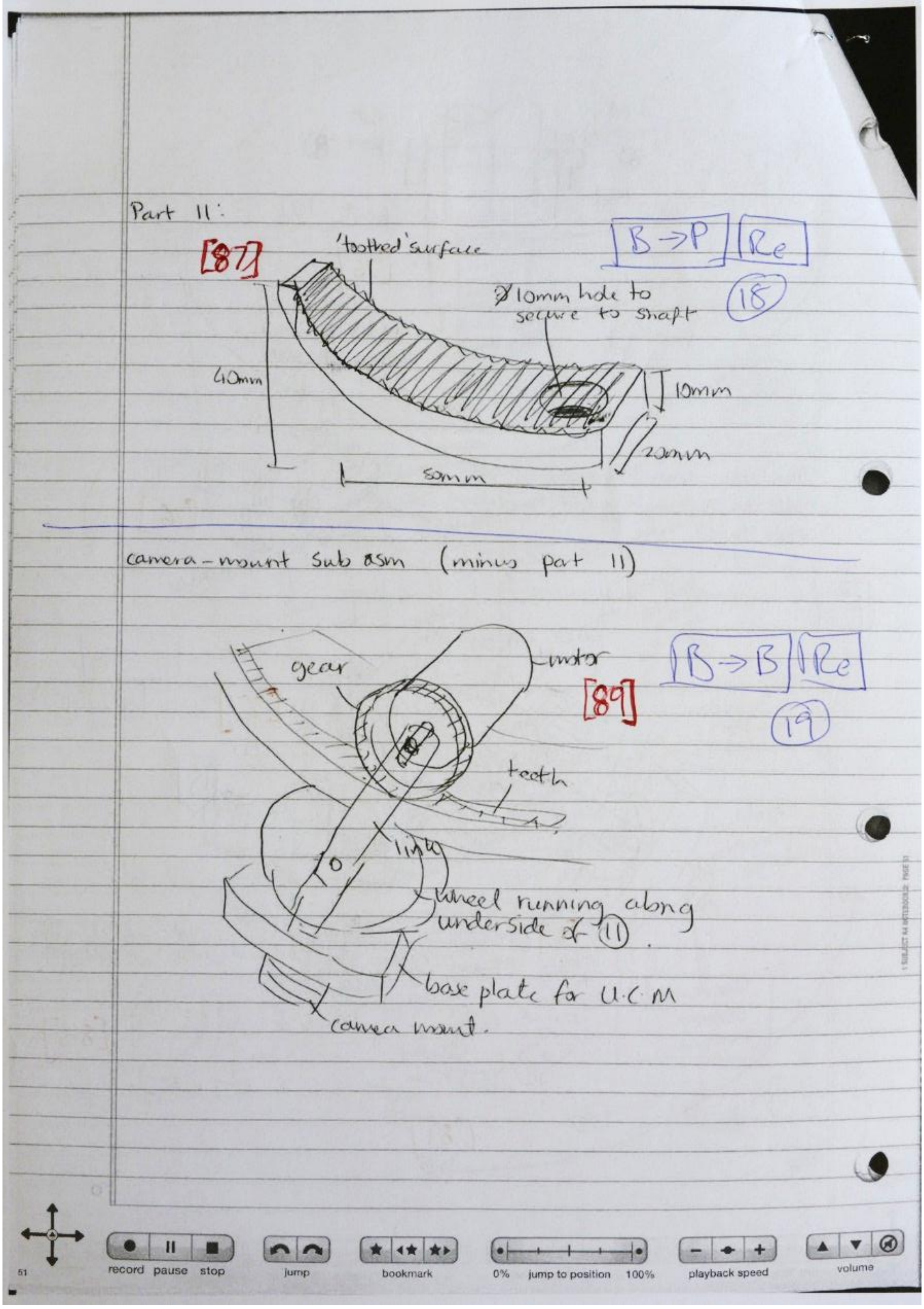
B→P Re
9

base plate must accomodate electronics/control systems etc. cannot be properly considered at this stage, but components can be roughly specified.: [50]


[53]
P→P Re 10
1. mounting brackets for motor:
x2:
2mm
50mm
38mm
6mm
14mm
Not to Scale.
Section A-A
R50 full rad.
90°
50mm
motor
1
2
M6 screws
wires
bent-aluminium plate
2mm thick.
2. base plate- polymer, laser-cut
[60]
P→P Re 11
4 OFF
Ø6mm thru' holes
6mm
[61]
common.
54mm
10mm
M6 tapped holes (thru') x4.
Ø12mm thru' hole
60mm
38 mm.
30mm
120mm.
4mm.
3. bush = M6 bush x 10mm; Ø6mm
[66]
plastic x4.
P→P Re 12
10mm
record pause stop
jump
bookmark
0% jump to position 100%
playback speed
volume
48


locked up gears
④-⑤ = Bevel pair to generate req. torque over 30 seconds.
I - not found
[68]
K
12mm hole
6mm shaft hole
P
K→P Re
13
bevel collar + grub screw ⑦.
plate 'hooks' over base plate to keep in position.
[71].
⑦. shaft:
[70]
location of base plate.
welded Ø16mm plate
aluminum Ø12mm
80mm
Ø6mm thru' hole.
10mm
B→P Re
14
[73]
⑧ hex bolt M6×24:
[72]
M6
24mm
K→P Re
15
⑬ bracket [74]
M6 hole
60
120
bent aluminum
B→P Re 16
49
record pause stop
jump
bookmark
0% jump to position 100%
playback speed
volume


Shaft (part 7)
Bolt part 8
Parts 4 and 5.
nut
(part 10).
[75]
part 11.
M10 Screw holding 10 to 11
gear
custom guide
motor
This was - panic! covered half the system + out of time - rough sketch time!
part 11
[76]
M10 bolt
F
gear to traverse custom track 11
2nd DC Motor
Cables from motor
F→B
Re 17
Space to clip on camera shutter release
axle
[77]
7
B
9
rigid connecting linkage
10
20mm
custom track 11 bolted on (M10)
wheel
[80]
(20mm plastic.
plastic mount to keep camera steady.
11
Universal camera mount
Custom track
60mm
90°
[83]
60mm
90°
[81]
record pause stop
jump
bookmark
0% jump to position 100%
playback speed
volume



Task 1 – The creation of a single layout (*behaviour* output) based on the brief and requirements provided in the previous study stage (*knowledge/function* input). No evidence of exploration in markings or video, hence restrained task.

Task 2 – Key functional sections listed (*function* output) based on brief and specifications (*knowledge* input). No evidence of exploration in markings or video, hence restrained task.

Deemed early-stage type task due to focus on functional solution principles rather than behaviour or structure.

Task 3 – Develop complete schematic (*behaviour* output) of design, based on functional requirements and discrete needs of the design (*function* input). Evidence of change from past versions in markings and exploration in video.

Task 4 – Selection of materials (*structure* output) for a number of components from design (*behaviour* inputs). Evidence of selection criteria that create additional benefit for the design beyond basic functional completion, hence an expansive task.

Task 5 – Selection of motor (*structure* output – occurs on video) based on knowledge of requirements and competitor products (*knowledge* input). Evidence of selection and exploration based on additional benefit to the design, hence and expansive task.

Task 6 – Produce numerical values for power requirements (*knowledge* output) based on the motor selected in previous task (*behaviour/structure* input). No evidence of exploration in markings or video, hence restrained task.

Task 7 – From discrete specifications and dimensions listed on motor provider website (*knowledge* input), record final dimensions of motor for sake of component interfacing (*structure* output). No evidence of exploration in markings or video, hence restrained task.

Task 8 – Based on decision to use bevel gears in task 3 (*behaviour* input), perform ratio calculations for selection of gearbox (*knowledge* output). No evidence of exploration in markings or video, hence restrained task.

Task 9 – Create a final layout, partially dimensioned, (*structure* output) of a single sub-system of the layout produced in task 3 (*behaviour* input). No evidence of exploration in markings or video, hence restrained task.

Task 10 – Produce final dimensioning for motor bracket (*structure* output) based on system layout in task 3, and motor dimensions in task 7 (*behaviour/structure* input). No evidence of exploration in markings or video, hence restrained task.

Tasks 11, 12, 14, 15, 16, 18 are identical to 10 in their transformation, as the designer completes the same activity for varying components in the design.

Task 13 – Design bevel gear arrangement (*structure* output) based on gearbox requirements in task 8 (*knowledge* input). Brief searching through manufacturer website, but determined to be solely for selection according to requirements rather than benefit or particular applicability to design. Selection abandoned quickly in favour of simple, restrained self-design.

Task 17 – Produced detailed layout of remainder of sub-system for camera mount (*behaviour* output). Several examples of evidence of building from requirements of design (e.g. clip for camera release), task input therefore labelled as *function*. No evidence of exploration in markings or video, hence restrained task.

Task 19 – Further layout of sub-system (*behaviour* output) from previous task based on past layout (*behaviour* input). No evidence of exploration in markings or video, hence restrained task.